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EXPERIMENTAL DESIGN IN THE EARTH SCIENCES

W. C. Krumbein

Abstract--Many Earth phenomena involve simultaneous change of several variables, usually not directly under man's control. Isolation of certain phenomena permits controlled laboratory experimentation, but there is also need for study of simultaneous natural variation in several factors, which in this context supplements rather than competes with laboratory experimentation. Statistical design provides a technique adapted to both laboratory experimentation and the observation of the effects of natural variations.

The present paper reviews the application of some statistical methods to the Earth sciences, with special reference to the design of experiments for analysis of variance. Consideration is given to the nature of distributions encountered in Earth science data, to sampling problems, and to some principles of experimental design. Geological examples are used, but parallels are drawn from other Earth science fields. The use of probabilistic models in developing Earth process theories is touched upon briefly.

Introduction--Statistics has a long history of applications in the Earth sciences. On a descriptive level, these include collection of observations on air temperatures, rainfall intensities, stream discharges, sedimentary particle sizes, and many others from practically all fields. The records are condensed in tables and graphs, and by computation of averages and other summarizing numbers. The summarized data serve many purposes in classification and comparison.

Summarizing operations constitute only part of the treatment of observational data. Statistical analysis affords many additional techniques helpful in sharpening subject-matter decisions. A difference between description and analysis is that whereas the observed numbers are used directly in descriptive statistics, in analytical statistics they are considered as a sample drawn from some larger population. Hence, it is appropriate to consider the kind of population involved and to demonstrate that the sample was in fact drawn from such a population. This point is emphasized by COURT [1952]. In analytic statistics, one attempts to make inferences about the population from a study of the sample drawn from it, while in descriptive statistics the aim is to give a concise description of the sample.

Laboratory experiments and field experiments--Application of statistical design in the study of Earth phenomena may be illustrated by comparing a conventional laboratory experiment with a corresponding field statistical experiment. It is known, for example, that average particle size of beach sand varies along and across beaches because of selective effects of waves and currents. This 'sorting process' may be studied in a laboratory wave tank with waves approaching an artificial sand beach at a fixed angle. The sand is selected for its known initial particle size and mineral composition. As the waves wash up on the beach, they select certain particles in terms of size, shape, or density, and move them preferentially along and across the beach. The period and height of the waves are varied in a systematic manner, and the changing properties of the sand along the beach are studied for each stage of the experiment.

The experimental data may be used to set up empirical relations showing the dependence of sand sorting on wave characteristics for the fixed angle of approach. Alternatively, a theoretical relationship based on wave energy or other considerations may be tested by the experiment. Scale-model theory may be involved.

The corresponding field experiment would be conducted on a straight segment of natural sand beach (Fig. 1), recognizing that natural waves vary in height and period, that the angle of approach changes seasonally or during storm cycles, and that the sand itself may have varying initial properties along the beach. These field conditions give rise to a variety of 'errors' which may seem to cast doubt on any results obtained. However, by designing an experiment in which the same variables (wave height, period, direction of approach) are the three main factors, with changing sand properties along the beach as dependent variable, it is possible statistically to separate the variability introduced by each main factor from the total variability, and to compare the individual variations with a combined 'error' term. The method for separating the variations is analysis of variance. Extension of the method to analysis of variance components permits evaluation of the

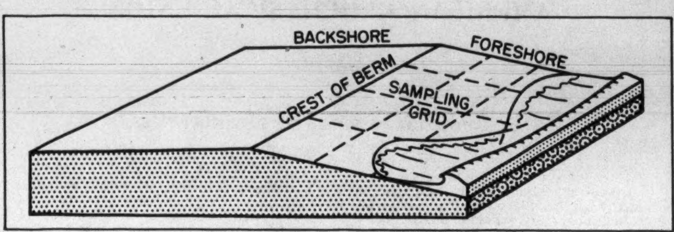

Fig. 1--Diagram of beach segment showing backshore, berm, and foreshore slope with sampling grid

relative contribution of each main factor to the sorting process. In fact, a mathematical statistical model of the beach, corresponding to the theoretical physical model, could be devised.

Comparison of the two methods for studying beach sorting indicates that they are complementary rather than competitive. The laboratory experiment requires rigid control of certain factors, which in turn requires simplifying assumptions when the theory is applied to natural beaches. The statistical model allows for the natural variations, but runs into the danger that the factors selected may not be the most important among all the factors introduced by nature, so that the somewhat simplified experiment may not be fully decisive. To the extent that the factors selected for study are important, however, a certain measure of predictability for beach processes becomes available. In the ideal case the experiments would permit better prediction of the effects of changes in natural sorting conditions imposed by engineering structures erected on the beach, for example.

The writer is not aware that a rigorously designed beach experiment of this type has been conducted. Sampling design is an essential part of the study, and this in part awaits fuller application of presently growing knowledge of beach particle size, wave, and wave-angle populations.

Although a knowledge of the 'population' or frequency distribution of a variate does not in itself give information on the laws governing a phenomenon, such knowledge is helpful in setting up sampling plans, in selecting experimental models, and in establishing confidence limits for population parameters. As an introduction to later discussion of the effects of different distributions on statistical analysis, some common distribution functions encountered in geological data are considered here.

Geological populations--Table 1 lists six common types of frequency distributions observed in geological data, with examples. The following brief paragraphs indicate the nature of the distributions and furnish references on each type.

The normal (Gaussian) distribution is commonly expressed as

$$y = (1/\sigma \sqrt{2\pi}) \exp\left[-(x-\mu)^2/2\sigma^2\right] \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where μ is the population mean and σ is the population standard deviation. DIXON and MASSEY [1951] provide an introduction to the properties of the normal distribution.

If the distribution of the variate x is such that ratios instead of differences are the important consideration [HERDAN, 1953, p. 113], the transformation $z = \log x$ may be made. Then if z is normally distributed, its distribution function is

$$y = (1/\sigma_z \sqrt{2\pi}) \exp\left[-(z-\mu_z)^2/2\sigma_z^2\right] \ldots\ldots\ldots\ldots\ldots \quad (2)$$

and the original variable x is log normally distributed.

The geometry of the normal curve is preserved in (2), which may be referred to as a log-Gaussian distribution. This geometry assures independence of the mean and variance, and permits complete specification of the curve by two z-parameters, which may be expressed in x-terms by taking antilogs.

Table 1--Examples of some distributions observed in geological data

Types of distribution	Example
Normal (or normal approximation)	Natural moisture content of beach sands Beach firmness Particle roundness and sphericity in some sediments Porosity of sediments Particle orientations over narrow range Percentages of abundant minerals in rocks Topographic relief in local areas Angle of slope along valley walls [STRAHLER, 1954]
Log normal	Particle size distribution in many sediments Lengths of first-order streams in drainage basins [STRAHLER, 1954] Thickness of varves [PETTIJOHN, 1949] Permeability of sedimentary rocks [LAW, 1944]
Circular normal	Particle orientations over wide range Orientation of cross-bedding in sands Rock fracture orientation [PINCUS, 1953]
Binomial	Abundant minerals in rocks (number of grains in subsamples of fixed size) Number of frosted grains in some dune sands (in subsamples of fixed size)
Poisson	Rare minerals in rocks (number of grains in subsamples of fixed size)
Gamma distributions[a]	Thickness of bedding in some sediments Percentage of organic content in some sediments Percentage of rarer chemical elements in rocks Sand-shale and clastic ratio in some facies data Particle-roundness and sphericity in some sediments

[a] Gamma distributions are derivable from Pearson Type III distributions by transformation.

The circular normal distribution is defined as

$$\psi(a, a_g, k) = \exp[k \cos(a - a_g)]/2\pi I_0(k) \quad \ldots\ldots\ldots\ldots\ldots (3)$$

where a is the angle variate, a_g is the angular co-ordinate of the center of gravity, k is a measure of concentration about the mean, and $I_0(k)$ is a type of Bessel function. GUMBEL, GREENWOOD, and DURAND [1953] give the theory and furnish tables.

The binomial distribution may be written as

$$P(x) = C_x^n p^x (1 - p)^{n-x} \quad \ldots\ldots\ldots\ldots\ldots (4)$$

where P(x) is the probability of x successes in n trials of an event for which p is the probability of success in a single trial and C_x^n is the combination of n things taken x at a time. The binomial distribution applies to discrete data, but it may be treated by the normal approximation when p does not depart too widely from 0.50.

The Poisson distribution also applies to discrete data when the probability of occurrence is very small. It may be written as

$$y = (m^x e^{-m})/x! \quad \ldots\ldots\ldots\ldots\ldots (5)$$

where m is the mean value. One characteristic of the Poisson distribution is that its mean and variance are equal. DIXON and MASSEY [1951] describe the binomial and Poisson distributions.

Gamma distributions appear to apply to continuous variates in which the asymmetry is greater than can be normalized by the log transformation. The Gamma function may be expressed in a number of ways; a one-parameter Gamma distribution may be written as

$$y = [1/\Gamma(P + 1)]\, x^P e^{-x} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

where $(P + 1)$ is the mean value, and $x > 0$. In this form the mean and variance are equal, and when $x = (P + 1) = m$, the function has the same value as the corresponding Poisson distribution.

The one-parameter Gamma distribution is skewed, and if $P = 0$, it reduces to the negative exponential $y = e^{-x}$. These are varieties of a more general class of Gamma functions forming a two-parameter family of distributions [MOOD, 1950, p. 112]. In Gamma distributions the mean and variance can be expressed as combinations of both parameters. This is in contrast to the Gaussian distribution where mean and variance are independent.

Other Earth-science distributions--It is instructive to compare the distributions in other Earth sciences with those observed in geology. The Transactions of AGU furnish abundant examples, and Table 2 is based largely on an examination of current and earlier volumes. (To save space in the reference list at the end, the full references are given directly in the Table.)

Table 2--Examples of some distributions from other Earth sciences (references to AGU papers give volume, page, year; others in bibliography)

Types of distribution	Example
Normal	Velocity distribution [KALINSKE, v. 26, p. 261, 1945] Water levels in wells [HUFF, pt. 2, p. 573, 1943] Geothermal gradients [LANDSBERG, v. 27, p. 549, 1946] Cloud drop sizes [suggested by HORTON, v. 29, p. 624, 1948]
Log normal	Hydrologic data [many references; see KIMBALL, pt. 1, p. 460, 1938] Some properties of [KALINSKE, v. 27, p. 709, 1946; also CHOW, v. 33, p. 278, 1952]
Circular normal	Theory [GUMBEL, GREENWOOD, and DURAND, 1953] Angle of wave approach; theory [COURT, 1952]
Binomial	
Poisson	Number of alpha particles emitted per unit time from radioactive rocks
Gamma distributions	Hail-damage frequency [DECKER, v. 33, p. 204, 1952] Height and period of ocean waves [PUTZ, v. 33, p. 685, 1952] Size of raindrops [HORTON, v. 29, p. 624, 1948] Hydrologic data [TODD, v. 34, p. 897, 1953, used log Pearson Type III]
Cube-root-normal	Rainfall data [STIDD, v. 34, p. 31, 1953]
Extreme values	Hydrologic data [GUMBEL, pt. 3, p. 836, 1941] Temperature data [COURT, 1952] Rainfall data [CHOW, 1953] Ocean wave amplitudes [LONGUET-HIGGINS, 1952]
Rayleigh distribution	Geomagnetic data [BARTELS, 1953] Ocean wave amplitudes [LONGUET-HIGGINS, 1952] Prediction of ocean waves [PIERSON, 1952]

Table 2 includes three distributions not listed in Table 1. The cube-root-normal law is apparently expressible in a cube-root-Gaussian form by expressing the mean and variance in terms of the variate $\sqrt[3]{x}$. The writer knows of no applications of this function in geology. The extreme value distribution is a type of double exponential which can be expressed in linear form by taking a double logarithm of the exponential form: $y = -\log[-\log F(X)]$. The theory was first applied to hydrologic data by Gumbel as indicated in Table 2. It is currently being extended to numerous geophysical fields. The writer is not aware of applications in geology, although the distribution offers possibilities in the study of unusually large boulders sometimes found in gravel deposits, to mention only one example.

The Rayleigh distribution is of basic importance in the study of periodic phenomena. It is a function of the type $y = (2/M^2)\, r \exp[-(r^2/M^2)]$, where r is a distance and M is a measure related to the spread of the curve. This function apparently has not been applied in geology, but it will be returned to in the closing summary of this paper.

The several frequency distributions described in this section show that many distributions are common to many fields. If a generalization is permitted, it would appear that the several Earth sciences can profit much by mutual discussion of their distribution functions. The need for co-operation with and guidance by mathematical statisticians is also explicit in this generalization.

Analysis of variance--The preceding two sections may seem to be digressions from the main theme of experimental design. As was stated, however, a knowledge of the kind of population from which samples are drawn is helpful in further analysis of the data. Some features of analysis of variance are included here for readers not familiar with the method, as a guide for further reading in such texts as SNEDECOR [1946], COCHRAN and COX [1950], MOOD [1950], DIXON and MASSEY [1951], GOULDEN [1952], and KEMPTHORNE [1952].

In its simplest form analysis of variance compares the variability between groups of data with the variability within the groups. As an example, suppose one were interested in determining whether the firmness of the beach in Figure 1 varied along the crest of the berm. One approach is to randomize a position on the crest, set a stake, and lay off additional stakes at, say, 100-foot intervals. Four or five penetrometer readings randomized about each stake would then supply equally spaced groups of data along the beach crest. Table 3 shows six groups spaced 120 ft apart along the beach at Wilmette, Illinois. Each group has five penetrometer readings.

Table 3--Variation in beach firmness along crest of beach at Wilmette, Illinois (smaller numbers mean greater penetrability), and analysis of variance

Penetration in station						Analysis of variance				
I	II	III	IV	V	VI	Source	Sum of squares	Degrees of freedom	Mean square	F[a]
21	31	30	47	52	38	Between groups	788	5	157.60	2.28 NS
52	42	27	38	44	40	Within groups	1660	24	69.17	.....
29	37	30	41	52	25	Total	2448	29	.....	.....
20	51	42	32	35	31					
30	44	46	41	48	39					
152	205	175	199	231	173					

[a] NS - Not significant.

In preparing to analyze these data, a null hypothesis is set up to the effect that there is no significant difference between the group means at the five per cent significance level. The experiment is accordingly designed to test for the occurrence of fixed relations among the group means.

The analysis of variance is given at the right of the data, computed in a manner described in DIXON and MASSEY [1951, p. 121]. The F ratio is computed by taking the ratio of the between-groups mean square to the within-groups mean square. The value 2.28 is less than the critical value of 2.62 for (5,24) degrees of freedom at the five per cent significance level [DIXON and MASSEY, 1951, p. 310] and hence the null hypothesis is not rejected.

One may conclude from this experiment that the beach firmness is homogeneous over the distance sampled, that is, all of the observations could have been drawn from a single firmness population. The mean value of all the observations 37.8 may be taken as an estimate of the population mean, and the within-group variance 69.17 may be taken as an estimate of the population variance. Inasmuch as the penetrometer readings are normally distributed (Table 1), confidence intervals for mean and variance may be readily computed [DIXON and MASSEY, 1951, pp. 74 and 108]. The 95 pct confidence limits for the mean are 34.7 and 40.9. The 90 pct confidence limits for the variance are 45.5 and 119.9.

Table 4--Analysis of variance, single factor basic form for k groups of n items each[a]

Source	Sum of squares	Degrees of freedom	Mean square
Between groups	$S(C_i^2/n) - CT$	$k - 1$	$SS_b/(k - 1)$
Within groups	By difference	$k(n - 1)$	$SS_w/k(n - 1)$
Total	$S(X_i)^2 - CT$	$kn - 1$	

[a] X_i is a single observation, C_i is a group total, S represents summation, CT is G^2/kn, where G is the grand total, and SS_b and SS_w refer to the between and within sums of squares.

The design used in this experiment is a single factor basic form. Its structure is indicated in Table 4; the notation is in terms of totals instead of means to indicate calculating machine computational procedures. The operation of separating the variability into two parts can be performed upon any sets of numbers, inasmuch as the method is based on algebraic identities [EISENHART, 1947]. The real question is, what use is to be made of the data after the variabilities have been separated? It is here that the concept of analysis of variance models comes in. In the paper referred to, Eisenhart discussed the assumptions underlying analysis of variance. His treatment is used in the following remarks.

The purpose of the firmness experiment was to determine whether there is any significant difference between the means of the firmness populations on the particular beach studied. The parameters thus were population means, and the model belongs in Eisenhart's Class I, used when the purpose is to detect the existence of fixed relations among population means.

In Class I models the estimates of population mean and variance are a form of the method of least squares, inasmuch as analysis of variance solutions are least square solutions. The main contribution of the method here is, according to Eisenhart, the standard form of Table 4, which simplifies the arithmetic and expresses the results clearly.

In contrast to a study of fixed relations among population means, analysis of variance may also be used to detect the existence of components of variance. In the firmness experiment the main interest was in a single beach, yet this beach is only a sample of the much larger population of all beaches. If interest had been focussed on detecting and estimating components of random variation in this larger composite population, emphasis would have to shift from consideration of fixed relations among means to consideration of random deviations in the characteristics of the Wilmette beach from the mean value of these characteristics in the larger population of all beaches.

This second model of the single factor form belongs to Eisenhart's Class II. It requires somewhat different mathematical assumptions, although the arithmetic is the same as in Class I models. A design of somewhat wider applicability, which can also be used for Class I or Class II purposes, is the row-column (two-factor basic) design. It is included here to extend the discussion to the use of grids as illustrated on the foreshore of Figure 1. EISENHART [1947] also uses it as his main example.

Table 5 illustrates the design. The X_{ij} represent single observations in each cell, and the row and column totals are indicated at the margins, a slight modification of Eisenhart's notation. In using this design for Class I problems, the X_{ij} are taken as random variables distributed about true mean values that are fixed constants. This is, if repeated observations are taken from the X_{ij} cell, they would vary at random about some fixed mean m_{ij}, which is the parameter that characterizes the X_{ij}. In using the design for Class II problems, on the other hand, the X_{ij} are taken as random variables distributed about a common mean value $m_{..}$, which is a fixed constant.

The mathematical relations of these models are not discussed here, except to point out that Eisenhart cites certain assumptions for each class of model. The population variance is assumed to be additive (that is, no significant interactions occur); correlations among the variables are

Table 5--Analysis of variance, row-column design for r rows and c columns, single entry form

Rows	Columns						Row totals
	1	2		j		c	
1	X_{11}	X_{12}	. . .	X_{1j}	. . .	X_{1c}	R_1
2	X_{21}	X_{22}	. . .	X_{2j}	. . .	X_{2c}	R_2
	. . .	. . .	. . .	. . .	. . .	. . .	. . .
i	X_{i1}	X_{i2}	. . .	X_{ij}	. . .	X_{ic}	R_i
	. . .	. . .	. . .	. . .	. . .	. . .	. . .
r	X_{r1}	X_{r2}	. . .	X_{rj}	. . .	X_{rc}	R_r
Column totals	C_1	C_2	. . .	C_j	. . .	C_c	G

Source	Sum of squares	Degrees of freedom	Mean square[a]	Estimate of
Between rows	$S\ (R_i^2/c) - CT$	$r - 1$	$SS_R/(r - 1)$	$\sigma^2 + c\sigma_R^2$
Between columns	$S\ (C_j^2/r) - CT$	$c - 1$	$SS_C/(c - 1)$	$\sigma^2 + r\sigma_C^2$
Residual	By difference	$(r - 1)(c - 1)$	$SS_e/(r - 1)(c - 1)$	σ^2
Total	$SS\ (X_{ij}^2) - CT$	$rc - 1$		

[a] SS_R, SS_C, and SS_e refer to the row, column, and residual sums of squares, respectively. X_{ij} is a single observation, R_i and C_j are row and column totals, S or SS represents summation, and CT is G^2/rc, where G is the grand total.

assumed absent, and the variances are assumed to be equal (Class I) or homogeneous (Class II). Finally, if the variables as defined for the two models are normally distributed, then all the analysis of variance procedures for testing means and estimating components of variance are strictly valid.

The lower part of Table 5 shows the computations for the row-column design, with the components of variance in the last column. In Class I use, the F ratios are obtained by dividing the row and column mean squares by the residual, and testing for significance. In Class II use, the components of variance may be estimated from the last column. For the row variance component, for example, the residual mean square is subtracted from the row mean square, and the difference is divided by the number of columns.

The analysis of variance designs presented here represent only two of a wide variety available for field and laboratory experiments. The reader is referred to the texts mentioned at the start of this section for further details.

Transformation of data for analysis of variance--Although normalcy of the data has some advantages in analysis of variance, the method itself is 'robust' enough to apply to fairly skewed distributions. COCHRAN [1947] discussed the consequences of failures to satisfy the assumptions of analysis of variance, and BARTLETT [1947] discussed ways of overcoming unsatisfied assumptions. When the data are distributed in certain non-normal ways, certain transformations are of value either for normalizing the data, or for stabilizing the variance. In addition, certain models with multiple cell entries can be used to separate out interaction effects (non-additivity) and to test them for significance.

In order to round out the discussion of distributions, Table 6 lists the six distribution functions of Table 1, and indicates some recommended transformations [BARTLETT, 1947]. Further discussion of the implications of transformations is given in SNEDECOR [1946], KEMPTHORNE [1952], and other texts referred to earlier. The writer is not certain about the need for transformations in circular normal distributions; and for Gamma distributions it may be that a square root transformation is of value for one-parameter cases as against a log transformation for two-parameter cases.

Table 6--Transformations used in analysis of variance

Distribution	Transformation	Remarks
Normal	None	
Log normal	Log X	Normalizes data
Circular normal	None (?)	
Binomial	Arc sine	Stabilizes variance
Poisson	$\sqrt{X}$	Stabilizes variance
Gamma	$\sqrt{X}$ or log X	Stabilizes variance (?)

Sampling designs--Inasmuch as statistical analysis treats a set of observations as a sample from some larger population, the sampling process itself becomes an essential part of experimental design. Only two aspects are touched upon here to continue the main thread of the paper.

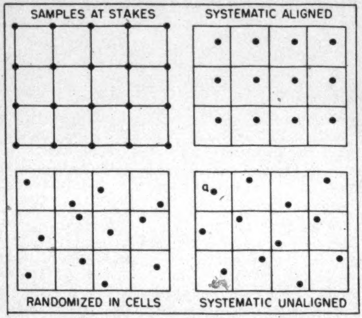

Fig. 2--Four ways of arranging samples in grid, adapted in part from QUENOUILLE [1949]

Figure 2 shows several sample layouts for a row-column grid of the type shown on the foreshore of Figure 1. QUENOUILLE [1949] describes these and other designs and discusses their relative efficiency under different conditions. The upper two diagrams have aligned systematic samples. In the upper left diagram the samples are collected at grid intersections, and in the upper right diagram the sample position was randomized in the first cell. The lower left diagram has its samples randomized in each cell, and in the lower right the samples are systematic but unaligned. For this pattern sample point a is randomized, succeeded by randomization of vertical co-ordinates in the remaining upper row cells, and randomization of horizontal co-ordinates in the remaining first column cells. COCHRAN [1953, p. 183] describes the process. Multiple samples from each cell may be had by repetition of the process.

If the foreshore is homogeneous over the grid, the randomized or aligned systematic samples are satisfactory, but if a population gradient is present, the unaligned systematic samples appear to bring out the gradient more effectively, as Quenouille points out.

The choice of grid cell size, the number of samples per cell, and selection of the randomization process depend to some extent upon the nature of the population being studied. Exploratory sampling plans, designed to bring out the main population characteristics, may be needed. With such exploratory data at hand, or with a background of qualitative knowledge, principles of stratification or systematization can be applied to the sampling problem.

A second approach to sampling, applicable to regional studies, is a hierarchical method in which large cells are successively divided into smaller units, in a manner illustrated in Figure 3, used by POTTER and SIEVER [in press]. The largest squares consist of nine townships each, and each township has 36 sections. Two townships are selected at random from each 'supertownship,' and in each of these two sections are selected at random. Finally, two wells are selected from each of the two selected sections. This method supplies a set of samples in a hierarchy, that is, such that the variance contribution of each level of sampling may be estimated. From such designs the proper spacing of samples for a particular objective (say very local versus broad regional studies) may be set up.

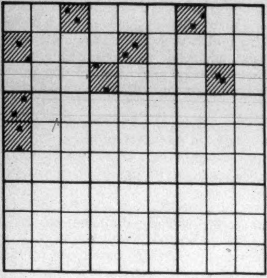

Fig. 3--Hierarchical sampling grid, partially developed; the large cells each consist of nine townships; the small black squares are sections; adapted from POTTER and SIEVER [in press]

A form of hierarchical method was used by YOUDEN and MEHLICH [1937] in a study of soil sampling. Stations were selected a mile apart, substations 1000 ft apart, sampling areas 100 ft apart, and sample points ten feet apart. The data permitted evaluation of the relative efficiency of various sample spacings. It was found that samples ten or 100 ft apart were too close together to constitute an effective method for sampling.

Earth science problems may require collection of data through time, over an area, or both. An example of the wide range of sampling designs available is given by WILM [1943], who described an ingenious design for sampling rainfall with portable equipment. Wilm used a randomized block design which involved stratification of the time period into sub-periods, and stratification of the area into sub-areas. For each time stratum he took two observations at random in each areal stratum with two portable instruments. These were moved about according to plan so that all areal strata were sampled at the end of each time stratum. This experiment gave average values within a few per cent of the values obtained by using ten times as many observations from gages at fixed locations. Wilm's plan has many applications where expensive equipment may be involved, or where it is desirable to allow flexibility in the sampling locations.

Design of experiments--The foregoing discussion of distributions, analysis of variance designs, transformations, and sampling are all related to the broader subject of experimental design. Although these topics were only touched upon, it is hoped that they serve to illustrate the theme of this paper, which is that there can be a sequence of steps in organizing experiments in fields where the number of variables is large, and where relatively few of them can be completely controlled.

Experimental design was first developed in agriculture and biology where control of the variables is limited. As the subject grew it was realized that the same principles apply to controlled laboratory experimentation. Perhaps the main contribution of experimental design was to free experimentation in any field from the somewhat rigid framework of classical laboratory investigation. YOUDEN [1951], in a book addressed to chemists, provides numerous examples of experiments which are improved by explicit recognition of the design elements inherent in them.

The subject of experimental design has received much attention, and the following remarks are based mainly on FISHER [1949], JOHNSON [1949], COCHRAN and COX [1950], YOUDEN [1951], and GOULDEN [1952]. Most writers agree that at least three related principles are involved. First, randomization must be an integral part of the design, to avoid bias. Randomization may be woven through the experiment at several stages, as in sampling, in selection of samples for particular tests, in choice of analysts for part of the work, etc. Many methods are available, from simple coin-tossing to tables of random numbers [DIXON and MASSEY, 1951, p. 290].

Replication assures that the experiment is self-contained, that is, that it provides adequate data for evaluation of its own results. YOUDEN [1951] discusses the importance of replication in some detail.

In many instances the scope of an experiment can be enlarged by permitting simultaneous variation of two or more factors. An example of this is the simultaneous testing of several samples by several analysts using several techniques. Selection of a proper design permits estimation of the variance ascribable to samples, operators, and techniques in a single experiment.

Advances in experimental design, especially in simultaneous variation of several factors, open additional opportunities for parallel field and laboratory investigations in the Earth sciences. These may be particularly appropriate when certain variables can be isolated for laboratory studies while other less controllable factors are concurrently investigated in the field. Examples could be drawn from the study of beach characteristics as developed earlier, in which field experiments including several natural factors supplement detailed laboratory studies of specific controllable variables.

WILM [1952] has recently integrated the principles of design into a pattern of scientific inquiry for applied research, illustrated with problems from forestry. The method is general and has definite applications in other Earth sciences. In essence the pattern includes logical analysis of the variables concerned; exploration of the problem through literature and other sources; experience represented by personal observation; and formal experimentation based on principles of design. The steps follow in sequence in complex problems, but in some inquiries the solution may be obtained at an intermediate stage.

Concluding remarks--The main thread of this paper led to design of experiments based on analysis of variance. This aspect of design is largely concerned with problems of estimation and hypothesis testing. The general method represents one of the most successful branches of analytical statistics.

Although analysis of variance, as applied to the beach experiments, would permit estimation of the relative contributions of several factors in beach processes, the method itself would not directly yield a dynamic theory of the processes. Such a theory would have to be developed by the methods of classical mechanics, or by establishing a statistical analogue of the physical model.

The basis for the statistical approach is that many natural phenomena are subject to random fluctuations, such that no strictly deterministic model can completely predict future events. The statistical model assigns appropriate probabilities to the events and thus makes its predictions on a probabilistic basis, within some selected confidence interval. The investigation of random processes from this point of view has come to be known as the study of stochastic processes.

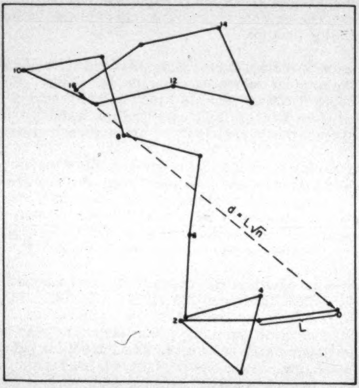

Fig. 4--Random walk with 16 steps; indicated distance d is expected value when many objects start from same origin

The probabilistic analysis represents an application of the theory of the 'random walk,' which underlies the Rayleigh distribution mentioned earlier. Figure 4 is a diagram of such a random walk, somewhat analogous to Brownian movement. It was prepared from a table of random numbers, as described by **BARTELS** [1935]. If many such diagrams were drawn, the mean distance of the objects from their initial position would approach the length of a step times the square root of the number of steps.

An example of such an approach to diffusion processes is given by **McEWEN** [1950]. The displacement of small objects in water from an initial point was regarded as the resultant of a large number of small positive and negative movements following probability laws. The frequency of the resultant displacement and the variance of the positions of the objects were obtained from a limiting form of the binomial series. The underlying theory for the general method is also developed by **FELLER** [1950].

McEwen's statistical development is analogous to the solution of the differential equation for diffusion. The constants of the diffusion equation are equated to the parameters of the statistical model, which thus provides a statistical solution of the physical problem.

The writer is not prepared to discuss stochastic processes in detail. The interested reader is referred to papers by **BARTELS** [1935], **LONGUET-HIGGINS** [1952], and **PIERSON** [1952] for additional examples. Bartels discusses the random walk in some detail and applies the theory to geomagnetic data. Longuet-Higgins used the Rayleigh distribution as a model for ocean wave amplitudes. Pierson applied Gaussian processes to the study of ocean waves, based on a model developed by **TUKEY** and **HAMMING** [1949] for analysis of noise in electronic circuits. By using samples of short duration, the assumptions of independent phases during steady state conditions of the sea surface were satisfied, and the analysis became analogous to the random walk problem.

These examples of stochastic processes are touched upon here because they will unquestionably gain in importance in the Earth sciences. The large number of variables in even the simplest Earth process, combined with the apparently random fluctuations which they display, provide a 'natural laboratory' for development of probabilistic models. Analysis of variance, in its usefulness for estimating components of variance and in testing hypotheses, provides an important step toward the ultimate goal of relating observations in nature to their underlying dynamic models of behavior.

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THE PROBLEM OF CALIBRATING HIGH-RANGE GEODETIC-TYPE GRAVIMETERS

G. P. Woollard, N. C. Harding, and J. C. Rose

Abstract--Various methods for the calibration of gravimeters are considered and discussed in terms of the potential and actual accuracy of calibration obtained. Comparative data are given for different types of gravimeters calibrated by the same method and for the same type of gravimeter calibrated by different methods. The uncertainties in calibration are shown to be the major factor determining differences in gravimeter values reported by different investigators.

Introduction--The problem of calibrating gravimeters is an old one and several methods of calibration have been tried and are currently used. These methods may be divided into four categories: (1) Calibration in tall buildings on the basis of the theoretical vertical gravitational gradient with suitable corrections for local mass effects. (2) Calibration on the basis of reoccupations of sites for which there are pendulum gravity measurements covering a large change in gravity. (3) Calibration by statistically averaging the results obtained for numerous ties between two points whose gravity interval is well established. (4) Calibration on a tilt table on the basis of the equivalent gravity effect of a known angle of tilt.

All of the above methods are theoretically sound, and if the parameters involved are known to the required accuracy, all presumably would give an identical true calibration value. Unfortunately, the uncertainties are such that, until 1953 at least, no calibration was possible that would permit an accuracy of measurement better than ±1.0 to 2.0 mgals for a 1000-mgal change.

While a calibration of this order of accuracy is more than adequate for a prospecting-type instrument having a range of 50 to 100 mgals, it obviously is not sufficient for making intercontinental measurements involving changes of 1000 mgals or more with high-range geodetic-type gravimeters.

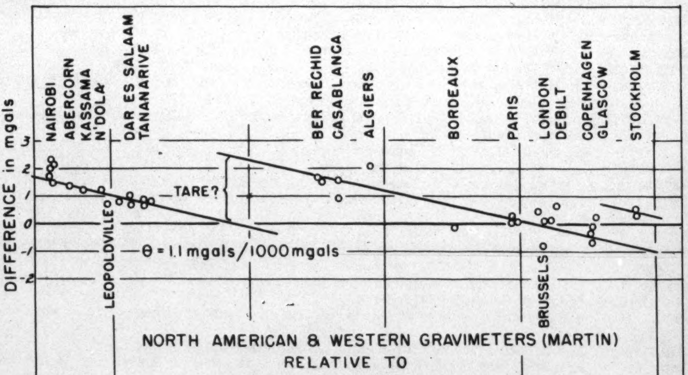

Fig. 1--Difference in values, Europe and Africa

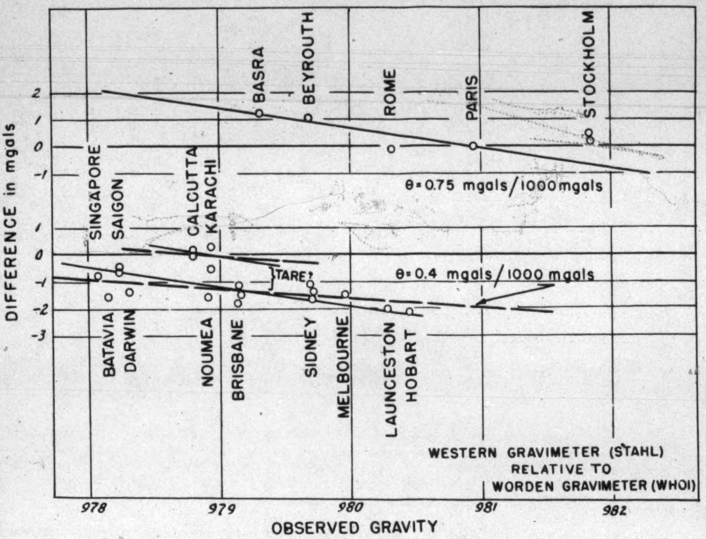

Fig. 2--Difference in values, Asia and Australia

At present there are about 50 such high-range gravimeters in use and five groups at least are carrying out measurements on what might be called an intercontinental basis and two groups working on a global basis. Because of differences in calibration, the results of these various sets of measurements appear to be widely divergent in some locations while in substantial agreement in others. That the difference is not attributable to errors, but rather to the calibration of the instruments used is indicated in Figure 1. In this figure, the differences in values obtained in Europe and Africa by the Expeditions Polaires Francaises [MARTIN, 1951; DUCLAUX and MARTIN, 1951] relative to those secured by the Woods Hole Oceanographic Institution [WOOLLARD and Others, 1952] are plotted. From this plot it is seen that a systematic departure in values of about - 1.1 mgals per 1000-mgal change in gravity is suggested with a mean deviation of ±0.3 mgal for 32 points covering 4200-mgal range. A similar plot in Figure 2 for results obtained in Australia and Asia [STAHL, 1954] suggests a departure of - 0.4 mgal per 1000-mgal change in Australia and - 0.75 mgal per 1000-mgal change in Europe. On both figures datum shifts are indicated which presumably are related to tares in one or the other set of values. In Figure 3, comparative values secured in North and Central America with different gravimeters [WOOLLARD and Others, 1953] are shown which indicate a systematic difference of about 0.6 mgal per 1000-mgal change.

Obviously, the gravimeters represented in these measurements were not all calibrated against the same standard. Actually, three different methods of calibration are represented. The meters used by Martin and Stahl were calibrated using the system of multiple runs between the Paris and Toulouse Observatories whose gravity interval is used as 499.90 mgals. The Worden meters that were used to give the reference values for the comparisons in Figures 1 and 2 were calibrated against gravity values established with the Cambridge University (England) pendulums in Australia and Great Britain. This was the same calibration standard used for Worden Meters 14 and 10e and North American Meter 113 in Figure 3. Worden Meter 10f was calibrated by tilt-table measurements. The primary problem involved here is which is the most reliable method of calibration, and the following discussion will be devoted to an analysis of the factors related to this problem.

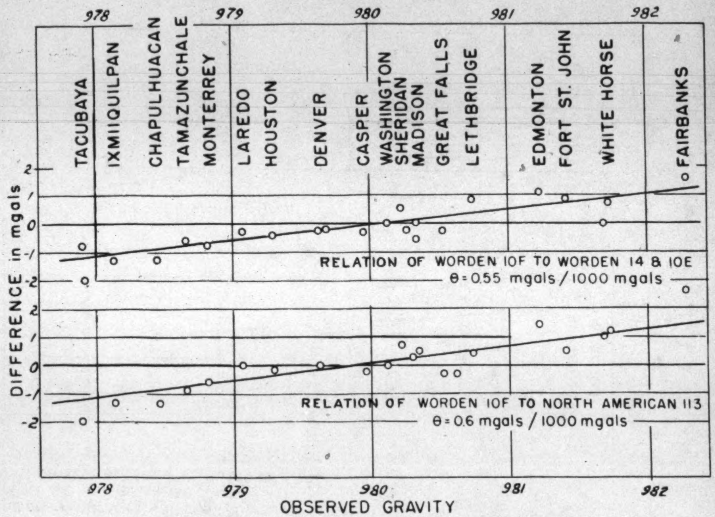

Fig. 3--Difference in values, Central and North America

Calibration on basis of vertical gravity gradient--In the early days of gravimeter calibration, it was thought that a satisfactory calibration could be achieved by making runs in tall buildings and relating the change in reading to the theoretical decrease in gravity with elevation. However, it was demonstrated [HAMMER, 1938] from results of tests conducted in the Cathedral of Learning Tower at Pittsburgh University and the Gulf Building in Pittsburgh, Pennsylvania, the Washington Monument in Washington, D. C., and the Empire State Building and the Chrysler Building in New York City that the observed changes with elevation were not the same in the different structures. The spread in values relative to the theoretical change with elevation varied from - 1.2 to + 1.4 pct after correcting not only for mass effects associated with the building but also for the surrounding terrain. It was further shown that these local vertical gradient anomalies were related to the local subsurface mass distribution as reflected in the areal gravity anomaly values. Hammer concluded that these factors alone might cause a calibration error of several per cent.

Other more obvious defects in this method of calibration are the changes in height of a building with seasonal fluctuations in temperature which would give differences from the elevation data taken from construction drawings, and the uncertainty in readings at upper levels due to the sway of the structure under all but the quietest meteorological conditions. It also is observed that different instruments are more susceptible to slight motion than others and the sensitivity of some instruments is also affected by motion. All these factors coupled with the limited change in gravity that can be obtained in a building are arguments against this method except for the determination of an approximate calibration value.

Calibration by comparisons with pendulum results--Calibration through the direct reoccupations of pendulum sites and equating the change in gravimeter scale values to the changes in pendulum gravity values is one which at first glance would appear to be eminently satisfactory. However, it is found that the uncertainties in pendulum values frequently are so large that even with data covering a range of 1000 mgals or more, a satisfactory calibration cannot be achieved. Even in the United States with a network of over 1100 pendulum bases covering about 1400-mgal change in gravity, it has not been possible to get an adequate calibration by this method. The difficulty stems from several sources, chief of which are shifts in the base datum value. These shifts may be caused by changes in the periods of the pendulums while in the field, and since these changes in pendulum period are not obvious until periods are computed or an initial base is reoccupied, they may not be detected until the end of a field season. All pendulum operations of the U. S. Coast and Geodetic Survey prior to 1950 were conducted on this basis and the closure errors resulting from such changes in period had to be distributed throughout the season's work. This system of correcting for closure errors automatically introduces errors where there are none and only partially corrects for errors where they are real.

Another factor giving a shift in datum which was only recently discovered by the U. S. Coast and Geodetic Survey is associated with the use of columnar piers in making gravity observations. It was found that gravity observations made on the two-foot gravity piers in the Commerce Building in Washington are not reliable because of possible sympathetic vibrations set up in the pier by the oscillating pendulums. Since this effect is variable, fictitious closure errors and datum shifts are obtained. The end result has been that errors in the 1100 odd pendulum values published for the United States [DUERKSEN, 1949] are too great to permit an accurate calibration. Figure 4 shows a plot of the differences in U. S. Coast and Geodetic Survey pendulum values and gravimeter values obtained by the writers in 1949 while trying to calibrate a high-range gravimeter against these pendulum data.

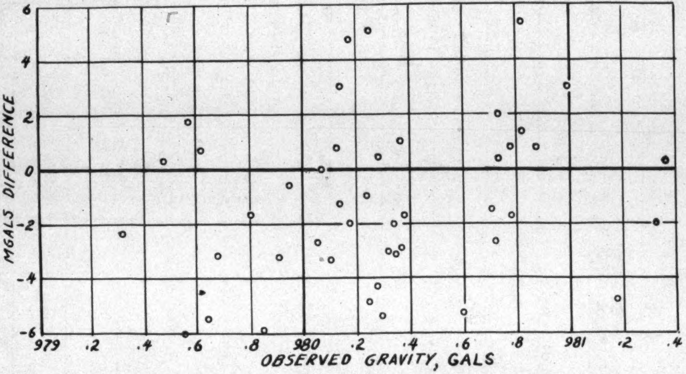

Fig. 4--Difference gravimeter and pendulum values, Midwest, North America

Table 1--Average deviation of gravimeter values from pendulum values, Midwest, United States

Year of pendulum work	Number of observations	Average deviation
		mgal
1890 - 1930	11	- 2.3
1932	5	+ 3.5
1934	6	- 3.3
1936 - 1939	5	+ 0.3
1940 - 1941	5	- 0.1
1948	4	- 2.1

Table 2--Mean deviation of gravimeter values from pendulum values, United States as a whole

Year of pendulum work	Number of observations	Mean deviations to nearest mgal
1870 - 1930	44	- 2
1932	18	+ 2
1933	15	+ 2
1934	10	- 3
1936 - 1937	44	0
1938	28	0
1939 - 1940	25	0
1941	4	0
1948	5	- 2

Much of the scatter in values shown in Figure 4 appears to be related to base datum shifts for work done in different years. In Table 1, an analysis is presented of the differences in values shown in Figure 4 in terms of the years in which the pendulum observations were made.

That the indications of table 1 are real is borne out by a more extended analysis of these gravity data taken from all parts of the country as shown in Table 2.

From Table 2, it is seen that the pendulum values established in the years 1870-1930, 1934, and 1948 are all two to three mgals too high. The values established in the years 1932 and 1933 all appear to be too low by about two mgals; and it is only for the period 1936 to 1941 that there appears to be no error related to a shift in base datum.

Half of the observed spread of ten mgals shown in Figure 4, therefore, is attributable to change in datum value and the remaining scatter of ±2 to 3 mgals is related to all other causes. This residual scatter in values is still too great to provide more than an approximate calibration having an accuracy of one part in 1000.

A similar attempt to use the global network of pendulum gravity stations established by Vening Meinesz as a calibration standard gave an equally bad scatter which is shown in Figure 5.

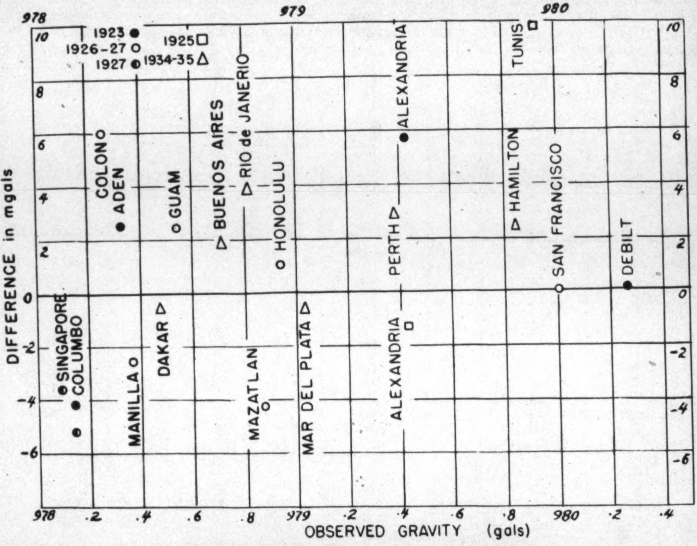

Fig. 5--Comparisons of Worden gravimeters and the pendulum gravity stations of Vening Meinesz

The first group of pendulum data that appeared to have a sufficiently restricted spread in values to permit their use for more precise calibrations and which covered any substantial change in gravity were those obtained with the Cambridge University pendulums. On the basis of the provisional values established with these pendulums in Australia and New Zealand and published values for Great Britain [COOK, 1950; BROWNE and Others, 1950], a calibration was determined in 1950 for gravimeters being used on a global basis by the authors which appeared to be good to better than one part in 3000. The mean deviation was ±0.5 mgal for over 3000-mgal change, when allowance was made for a tare of 2.4 mgals in the pendulum connection between England and Australia (see Fig. 6). This offset (tare) of about 2.4 mgals indicated by the gravimeter values in the pendulum interval between Great Britain and Australia appears to be real and recently was verified by the gravimeter measurements carried out by STAHL [1954] between Europe and Australia.

Even less spread in values was indicated when the series of U. S. Coast and Geodetic Survey gravity stations, especially established in 1950 for calibration purposes through the use of both pendulum and gravimeter observations, were occupied in 1952. As the gravity values used for this

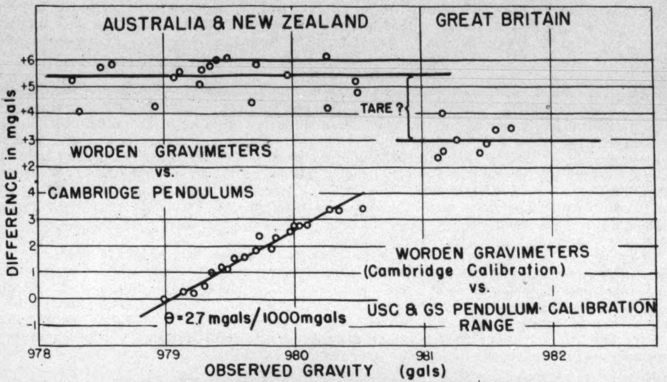

Fig. 6--Comparison of gravimeter values with Cambridge and USC and GS pendulum values

series of calibration stations were the result of an adjustment of the pendulum observations with gravimeter measurements made at the same time, the scatter in values about the mean is very small. The calibration established with these gravity values as a standard, though, showed a systematic deviation of - 2.7 mgals for 1000-mgal change from that obtained using the Cambridge pendulums as a standard (see Fig. 6).

The marked systematic departure indicated between the gravity results of the U. S. Coast and Geodetic Survey and those based on the Cambridge University pendulums is believed to be largely due to the difference in effects of changes of the Earth's magnetic field on the periods of the two respective sets of pendulum equipment. The Cambridge pendulums were magnetically compensated through the use of a Mu metal liner in the pendulum case and they were always oriented so as to swing perpendicular to the magnetic meridian, whereas prior to 1952, no provision was made for the effects of changes in the Earth's magnetic field on the period of the pendulums of the U. S. Coast and Geodetic Survey. Since both sets of pendulums were made of Invar, which is a ferromagnetic material, this difference in allowing for changes in magnetic field strength presumably resulted in an appreciable difference in the gravity values.

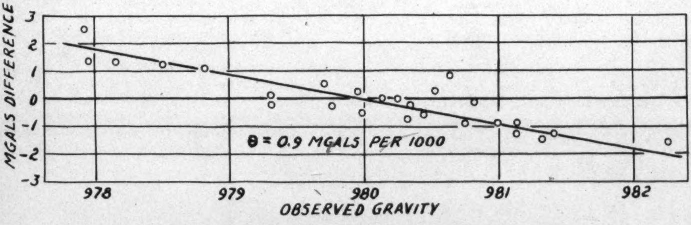

Fig. 7--Difference (Worden gravimeter Cambridge pendulum calibration) versus (Gulf M pendulums), 1953, Mexico - Alaska

The question naturally arises as to how complete was the magnetic compensation achieved with the Cambridge pendulums. This can be indirectly evaluated in terms of the differences in results obtained with gravimeters calibrated against the Cambridge pendulums and the provisional gravity values obtained with the non-magnetic quartz pendulums of the Gulf Research and Development Co. In Figure 7 the differences obtained on this basis are shown for a series of observations made between Mexico and Alaska in 1953 by the writers. This plot indicates that the calibration based on the Cambridge pendulums probably should be revised so as to give an increase of about 0.9 mgal for every 1000-mgal change.

The U. S. Coast and Geodetic Survey and the Dominion Observatory of Canada are also working on this problem. In 1953, the U. S. Coast and Geodetic Survey reoccupied key points along their gravity calibration range with their pendulums compensated for changes in the Earth's magnetic field through the use of a Helmholtz coil. The resultant change amounted to about +3.0 mgals for 1000-mgal change. During 1952 and 1953, also, the Dominion Observatory of Canada has been using the Cambridge pendulums with a Helmholtz coil and no Mu metal liner. Key points along the entire line of measurements established by the writers with the Gulf pendulums between Mexico and Alaska have been occupied with this equipment and also a new pendulum tie has been established between Europe and America.

To date, five sets of gravimeter observations between Mexico and Alaska in connection with this project have been made along with three sets of Gulf pendulum measurements, one set of Cambridge pendulum measurements, and a partial set of measurements with the pendulums of the U. S. Coast and Geodetic Survey. The pendulum control starts at Paso de Cortez, Mexico, where the provisional gravity value established with the Gulf pendulums is 977.5714 gals and terminates at Fairbanks, Alaska, where the provisional gravity value is 982.2457 gals. In between, there are 36 pendulum observation sites to furnish intermediate control.

Upon completion of the final computations for all of the observations that have been made (one complete set of Gulf quartz pendulum values has yet to be reduced), it is hoped that a gravity standard having an accuracy of one part in 5000 or better will be available for calibration purposes.

Calibration by method of multiple observations--This method, using multiple reoccupations of two points having a well-established gravity interval, is one that is used extensively in calibrating prospecting-type gravimeters. It has also been used to calibrate high-range geodetic-type instruments. With a relatively large change in gravity and numerous observations, the statistical average permits a calibration precision to be obtained that approaches one part in 2000. It has been observed though that different meters calibrated by the manufacturers using this method of calibration have shown considerable variation in results in observing a given large gravity interval. Even instruments built by the same manufacturer and calibrated against the same gravity interval have been observed to give differences as large as ten parts in 1000.

Perhaps the most exact calibration of this type that has been carried out is that described by MARTIN [1951]. In calibrating high-range North American and Western gravimeters to be used on the Expeditions Polaires Françaises, a provisional calibration was first established by reoccupation of the principal national gravity bases in Europe. To obviate effects resulting from the arbitrary adoption of national base values, this provisional calibration was based on the actual and indirect pendulum ties between each of the bases.

Using this calibration the interval between Paris Observatory and Toulouse Observatory was established as 499.90 mgals. All of the gravimeters were then calibrated against this standard interval by multiple reoccupations.

As is indicated in Figure 1, on the basis of comparative measurements, there is a systematic departure of - 1.1 mgals per 1000-mgal change between this standard and that based on the Cambridge pendulums in Australia and Great Britain.

Tilt-table calibrations--It is feasible to calibrate gravimeters having a small mass in terms of the equivalent gravitational effect for a given angle of tilt. The expression for Δg, the change in gravity for a given angle of tilt, is

$$\Delta g = g\,(1 - \sqrt{1 - h^2/L^2}) \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

where g = value of gravity at point of experiment
h = vertical displacement of the tilt table as determined with Johannson gage blocks
L = length of the tilt table (hypotenuse of the triangle) as measured between the hinge point and the point of rise

In making this measurement the instrument has to be oriented on the table so that the hinge line of the instrument element is perpendicular to the knife edge hinge of the table. In this position the instrument is stable and no change in sensitivity is obtained.

In carrying out the calibration the instrument is tilted both up and down by the same amount from the level position and the change in instrument reading noted. Observations are taken for a sufficient number of changes in tilt to cover the range of the spring, and the dial constant (calibration) K, for the spring is determined for a given change in dial readings ΔD as

$$K = \Delta g/\Delta D \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

In the case of the Worden meters which have two spring systems and two reading dials, the high-sensitivity fine-spring dial is calibrated first and the spring adjusted to give a linear calibration good to one part in 1000 over its full range.

The low-sensitivity, high-range, coarse-spring dial is calibrated over its full range of eight turns in about three stages. When both dials have been tilt calibrated in this way, the mass on the elastic system is then changed to increase or decrease the large dial reading. This simulates the effect of large changes of gravity associated with moving the meter north or south by 20-30° of latitude. The dial constants are then redetermined on the tilt table, and the process repeated until the full range of the large dial has been covered.

Changing the mass, however, changes the dial constants of the meter according to the following working formulas

$$\Delta D = M \times \Delta g \times S \qquad\qquad K = \Delta g/\Delta D = 1/M \times S$$

where ΔD = change in dial reading
S = strength of spring attached to dial
M = effective mass of system acted upon by gravity
Δg = change in gravity
K = dial constant in terms of some gravitational unit per scale division

The formula shows that the dial constant K is inversely proportional to a spring factor S and to the mass of the system M.

In the case of the small dial, the variations of, or the non-linearity in, the strength of its spring with changes in mass is very small for the following reasons: (1) The small dial spring is 'linearized' to hold variations in the small dial constant to about 1/1000 over the entire range of the small dial. (2) The meter is brought to the null line after a mass change by turning the large dial to increase or decrease the tension on the large dial spring as needed to center the pointer. Consequently the small dial spring remains at essentially the same length and at the same tension. Therefore, any variation in K of the small dial with shifts in mass is inversely proportional to the change in the mass and is not affected by the non-linearity of S for the small dial spring. Hence the small dial constants for each calibration run can be used in the form of corrective ratios to relate the large dial calibration obtained after each change in mass to the calibration determined after the final mass adjustment. This last adjustment is required to give the instrument the proper dial range north and south of the point of calibration.

Ties with several tilt-calibrated gravity meters to gravity bases ranging in latitude from Paso de Cortez in Mexico to Fairbanks, Alaska, indicate that the tilt calibration using this technique is good to one part in 2000. Slight errors of this magnitude are probably caused by bending of the tilt table at high angles, minute variations in the tilt table knife edges, errors introduced by small screw curve effects, and possibly by tiny shifts in the center of mass of the elastic system as the meter is tilted.

Figure 8 shows calibration curves as determined by this method for the high-range spring dials on two geodetic-type gravimeters. On one instrument, Worden 32, the response appears to be flat and linear while on the other instrument, there is a well-defined change in calibration constant with change in range. These curves bring out quite clearly one inherent advantage of the tilt-table method of calibration, namely, that the linearity of response of an instrument can be checked over its entire range in the laboratory.

Instrumental factors affecting calibration--Although it is usually assumed that an instrument has a linear response over its entire range, this is frequently not the case. An extreme example

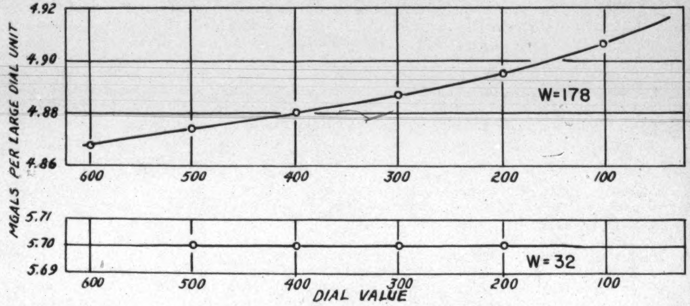

Fig. 8--Gravimeter tilt-table calibrations

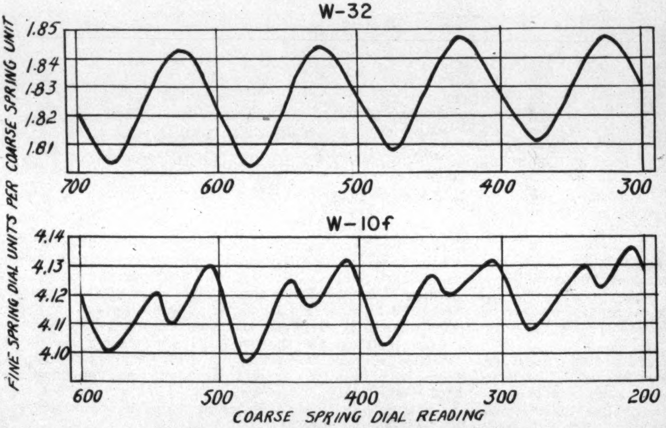

Fig. 9--Gravimeter anomalous response curves

of non-linearity was that obtained with one of the 'zero length'-type, high-range gravimeters which, when checked against a series of pendulum bases, showed a sudden departure in values that accumulated to 30 mgals before the tests were stopped. Such departures from linearity are related to the instrumental spring system, but in addition, there are calibration abnormalities which result from less obvious causes. Chief among these are irregularities in the pitch of the screw on the dial shaft to which the spring is attached, irregularities in the divisional markings on the reading dial, and eccentric mounting of the dial on the screw shaft. These factors may give what appears to be a simple sine curve variation in the calibration of the spring dial for each revolution or a more complex variation as shown in Figure 9. Failure to detect these abnormalities and to correct for them may result in errors of a mgal or more in measuring a given gravity interval. That these factors are present to some degree in all gravimeters is inevitable. Of the best obtainable screws tested by one gravimeter manufacturer, over 75 pct are rejected because pitch irregularities would give reading variations exceeding 0.2 mgal if used with a high-range spring.

Similarly, few reading dials when laboratory tested prove to have identical spacing of the division markings. Also since all dials have to be attached to the spring screw shaft either through a keyway or set screw arrangement, it is practically impossible to eliminate eccentricity completely.

On low-range, high-sensitivity spring systems, the above defects are of negligible importance, but on a high-range system where one revolution of the dial may be equivalent to anything from 100 mgals to 500 mgals or more; these defects become very important.

In the case of the Worden instruments, abnormal effects can be detected on the tilt table and their nature determined and the screw repolished, or replaced if the errors are too large. These same defects can be detected by field measurements with this type of instruments since through the use of two spring systems with independent reading dials, the effects on the high-range spring dial can be evaluated in terms of changes on the low-range spring dial. That is, by taking readings on both dials for two or more settings of the coarse-spring dial at any one place, the equivalent number of fine-spring dial units per coarse dial division is obtained. By repeating this reading process at places where the gravitational attraction differs progressively, the entire range of the coarse-spring dial can be covered. A plot of the variation in equivalent fine-spring dial units per coarse dial units as shown in Figure 9 defines the abnormalities associated with the coarse-spring dial and its screw. Such a plot is referred to as the 'screw curve' or 'abnormality curve' for the coarse-spring reading dial of the instrument.

That a field calibration based on comparisons against pendulum values or multiple ties between two bases, or a laboratory tilt-table calibration could be appreciably in error because of the reading dial abnormality curve is indicated by Figure 10. In this figure, the solid curve represents the coarse-spring reading dial abnormality curve which has a sine wave form. The dashed curves represent the cumulative error resulting from the assumption of a constant calibration value for an instrument when the actual calibration varies because of the (solid line) abnormality curve. If a calibration were started at a dial reading corresponding to Point A, the mean error curve obtained for the calibration would have the form of dashed Curve A, which averages a positive value so that the resulting calibration factor would be too large. If the calibration were started at a dial reading corresponding to Point B, then the mean error curve would have the form of dashed Curve B and the average resulting calibration would be essentially correct. If the calibration were started at a dial reading corresponding to Point C, then the mean error curve would have the form of Curve C and the resulting average calibration would be too low.

From an inspection of the curves in Figure 10, it is clear that the amount of the calibration error related to the abnormality curve of the coarse-spring dial will vary with the number of calibration points used, the differences in gravity involved relative to the base value, and the

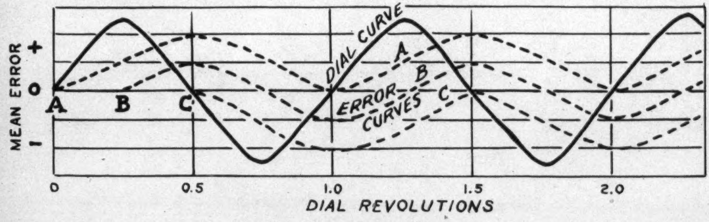

Fig. 10--Relation of mean error to dial curve

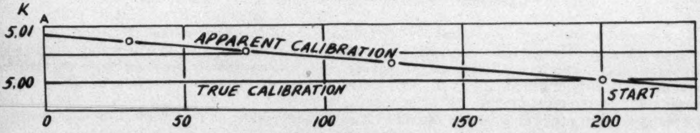

Fig. 11--An effect of dial curve on calibration, starting at A relationship of these calibration increments to the abnormality curve of the particular instrument involved. Since a relatively small number of calibration values are commonly used, the sinusoidal pattern of error curves A, B, and C shown in Figure 10 is seldom apparent. The usual pattern is an apparent random scatter of points whose mean usually indicates a flat calibration. A non-linear or sloping calibration curve, however, can also be obtained that may be fictitious. Such a pattern results if a calibration, for instance, is started at a point corresponding to Point A on the abnormality curve and the calibration increments chosen all happen to have reading dial values associated with them, which have essentially the same cumulative reading dial error. For example, assume an instrument is tilted the equivalent of a change of 375 mgals from the A position with a coarse-spring dial change of 74.9 divisions. The cumulative error due to the abnormality curve for 74.9-division change is 0.1 scale division, and the correct dial reading should be 75.0 divisions. The apparent constant is therefore 375/74.9 = 5.007 mgals per division instead of 5.000. The same amount of error (0.1 scale division) would also be obtained for tilts from the A position of 750 mgals, 875 mgals, 1100 mgals, and 2125 mgals. The respective dial readings would be 149.9, 174.9, 224.9, and 424.9 instead of 150, 175, 225, and 425. The calibration constants so determined for these increased increments of tilt would progressively decrease from the value of 5.007 for a tilt corresponding to 375 mgals to 5.001 for a tilt corresponding to 2125 mgals, and the resulting curve would show a non-linear form. A straight line graph having a slope as shown in Figure 11 would result if the tilt increments resulted in a linear decrease in the cumulative dial reading error.

To guard against such effects in making a tilt-table calibration, it is now customary to make the degree of tilt correspond to gravity increments that will give full revolutions of the reading dial and to start calibration measurements from points corresponding to the B (peak value) positions on the abnormality curve of the reading dial.

In carrying out calibrations based on pendulum measurements, the writers experimentally determine the reading abnormality curve for the high-range spring dial on the Worden instruments used over their entire range and integrate the abnormality effect of the dial so as to obtain equivalent fine-spring dial units for any reading of the coarse-spring dial. The calibration is then established in terms of fine-spring dial units.

As to how well the calibration constant for an instrument based on this method as determined by tilt-table measurements for the fine dial constant checks with that based on field observations using the Gulf pendulum measurements between Mexico and Alaska as standard is indicated by the difference curve shown in Figure 12. A weak slope of 0.03 mgal per 1000 mgals is indicated and since the mean deviation is of the order of ±0.3 mgal over the 4500-mgal range covered, it may be questionable as to whether this slope is real or not.

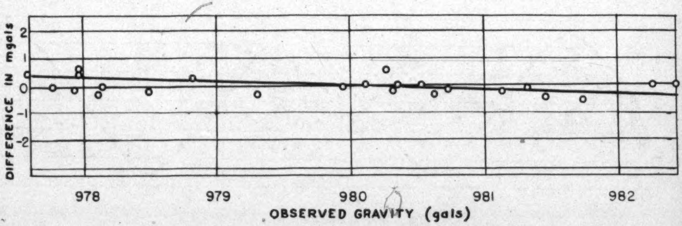

Fig. 12--Difference, W-10f and Gulf M pendulums, Mexico - Alaska

Evaluation of calibration methods--It is not possible at this time to make a definite evaluation of the accuracy of the various calibration methods since as yet there is no universally accepted standard against which results can be compared. The relative gravity measurements carried out with different sets of pendulums over large distances still do not appear to agree to better than one mgal for 2000-mgal change. Whether this discrepancy is caused by a tare in the results or a systematic effect peculiar to one of the sets of pendulums cannot be said without further check measurements. Neither can existing absolute gravity values be used to establish a standard. The discrepancy in the Potsdam absolute value appears to be of the order of 17 mgals, and the Bureau of Standards absolute value in Washington, D. C., and that at the National Physical Laboratory at

Teddington, England, give an interval that appears to be about 5.0 mgals in error on the basis of relative measurements carried out with both pendulums and gravimeters.

All that can be done at the present time is to compare results obtained using various gravity standards and note the differences present. On this basis the following relations between calibration standards appear to hold:

Paris Observatory - Toulouse Observatory standard versus Australian - Great Britain Cambridge pendulum standard: (-) 1.1 mgals per 1000-mgal change.

Tilt-table standard for fine-spring dial with integrated coarse-spring dial equivalent in fine-spring dial units versus Australian - Great Britain Cambridge pendulum standard: (+) 0.6 mgal per 1000-mgal change.

U. S. Coast and Geodetic Survey calibration range (1950 values) standard versus Australian - Great Britain Cambridge pendulum standard: (-) 2.4 mgals per 1000-mgal change.

U. S. Coast and Geodetic Survey pendulum (with Helmholtz coil) standard versus Australian - Great Britain Cambridge pendulum standard: (+) 1.2 mgals per 1000-mgal change.

North American Cambridge pendulum with Helmholtz coil standard versus Australian - Great Britain Cambridge pendulum standard: (+) 0.6 mgal per 1000-mgal change.

Gulf quartz pendulum standard versus Australian - Great Britain Cambridge pendulum standard: (+) 0.9 mgal per 1000-mgal change.

It is perhaps significant that the present method of tilt-table calibration and the pendulum results obtained with magnetic compensation as well as those obtained with the quartz pendulums all indicate a higher calibration than has been used to date in making intercontinental gravity studies. Although the exact amoung of increase indicated varies between 0.6 mgal and 1.2 mgals per 1000 mgals, with an average of approximately one mgal per 1000 mgals, it is not so important at this time to establish an exact calibration standard as to have a universally accepted standard. With the large amounts of gravity data now being secured with gravimeters on a world-wide basis and the increasing number of problems being studied through the use of gravity, it is essential that the values being obtained by all groups be put on an equivalent basis. As things stand with a known difference in calibration standards in use of about 2.5 mgals per 1000-mgal change, there cannot help but be confusion in the use of gravimetric data and the possibility of erroneous results in certain studies incorporating these data.

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NOL VECTOR AIRBORNE MAGNETOMETER TYPE 2A

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Abstract--The NOL vector airborne magnetometer type 2A (VAM-2A) measures the direction and intensity of the Earth's magnetic field from aircraft. Like the earlier type 1A, it continuously records the total intensity of the field and the magnitudes of a number of angles which specify its direction, but the 2A can be used in all latitudes and requires fewer steps in the reduction of results. Electronic circuits are used to average continuously the always varying angular magnitudes over predetermined intervals of time so as to minimize errors arising from the deflection of the pendulously suspended magnetometer mechanism by accelerations of the aircraft. The total-field measuring system of the magnetometer has a temperature coefficient of about $0.5\gamma/^\circ C$. Drift due to causes other than temperature change is about one gamma in 12 hr. Magnetic compensation virtually eliminates the necessity for correcting the data for the field of the aircraft. In a region where the angle of dip is about 60°, F, H, Z, I, and D are measured under average conditions with estimated probable errors of 15, 40, and 30 γ and three and five minutes of arc, respectively.

Introduction--The NOL vector airborne magnetometer type 2A (VAM-2A) is the second model of an instrument developed by the Naval Ordnance Laboratory for surveying the direction and intensity of the Earth's field from aircraft. The first model, the NOL vector airborne magnetometer type 1A (VAM-1A), has been described in the Transactions [SCHONSTEDT and IRONS, 1953].

Both the VAM-1A and the VAM-2A measure the total intensity of the field and angles which specify its direction. Both instruments employ pendular vertical references. In the VAM-1A system, the field-sensing mechanism (orientor) is rigidly secured to the aircraft, and the direction of the field measured with respect to the orientor is corrected mathematically for the off-level orientation of the aircraft (or, in other words, referred to vertical) by employing the pitch and roll angles obtained by continuously recording the angular displacement of a pendulum about the two axes of its supporting gimbals.

In the VAM-2A system, the orientor itself is suspended from gimbals as a pendulum, and the field vector is measured directly with respect to this vertical reference. Since two fewer angular measurements are required with the VAM-2A, the equations which express the components of the field are much simpler than those for the VAM-1A. The VAM-2A is a considerable improvement over the VAM-1A, owing not only to the refinement of basic apparatus common to both magnetometers but also to the addition of several new features.

A later design version of the VAM-2A known as the VAM-2B is essentially identical with the 2A except that newer types of components are specified for the type 2B. The description which follows applies equally to the 2A and 2B magnetometers.

What the VAM-2A measures--The determination of the field vector with the VAM-2A involves the measurement of (a) the total magnetic field intensity, (b) two angles which establish the direction of the field with respect to the orientor mechanism, and (c) an angle which specifies the attitude of the orientor mechanism in azimuth relative to a celestial body. Except for a possible lubber-line error, this angle is the relative bearing of the aircraft.

With the above measurements and such additional information as Universal Time, the latitude and longitude of the aircraft, and astronomical data, the field vector can be computed for points along the flight line.

Measurement of the total field intensity--The VAM-2A field-sensing and detector-orientation circuits are of the general type used in the AN/ASQ-3A airborne magnetometer employed for geophysical exploration, which was developed by the Bell Telephone Laboratories [FELCH and Others, 1947; RUMBAUGH and ALLDREDGE, 1949]. The VAM-2A servomechanism circuits are practically identical with those of the ASQ-3A system. The VAM-2A field-measuring circuit, however, differs in several important respects from that of the ASQ-3A. The distinguishing features of the VAM-2A circuit consist of a feedback-loop arrangement for measuring the variations of the field intensity, a battery-stabilized vacuum-tube power supply for the direct current which neutralizes the bulk of the field in the inductor, and the use of metal spools for the inductors. The spool of the field-measuring inductor is made of titanium on account of this material's low thermal expansion and low magnetic susceptibility. The most critical eddy-current path of the spool is broken by a radial saw slot cut along its entire length.

Figure 1 is a block diagram of the 2A field-measuring circuit. The inductor winding is energized by a 1000-cycle sine-wave current generated by a vacuum-tube oscillator. A 1000-cycle band-pass filter following the oscillator presents a very high impedance to frequencies that are harmonics of 1000 cycles, so that they do not reach the inductor in significant amounts.

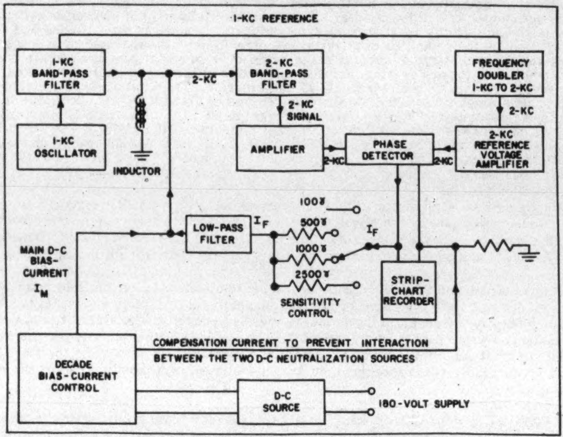

I-KC REFERENCE
I-KC BAND-PASS FILTER
2-KC
2-KC BAND-PASS FILTER
FREQUENCY DOUBLER I-KC TO 2-KC
2-KC SIGNAL
2-KC
I-KC OSCILLATOR
INDUCTOR
AMPLIFIER
2-KC
PHASE DETECTOR
2-KC
2-KC REFERENCE VOLTAGE AMPLIFIER
100γ
LOW-PASS FILTER
I_F
500γ
I_F
1000γ
2500γ
SENSITIVITY CONTROL
MAIN D-C BIAS-CURRENT I_M
STRIP-CHART RECORDER
COMPENSATION CURRENT TO PREVENT INTERACTION BETWEEN THE TWO D-C NEUTRALIZATION SOURCES
DECADE BIAS-CURRENT CONTROL
D-C SOURCE
180-VOLT SUPPLY

Fig. 1--VAM-2A field-measuring circuit

A second-harmonic signal (2000 cycles), generated in the inductor by reason of the presence of a field along its axis, is separated from the excitation voltage by a 2000-cycle band-pass filter. This 2000-cycle signal is amplified, phase detected, and fed back to the winding of the inductor in the form of a positive or negative direct current (I_f of Fig. 1). The magnetic field associated with the direct current reduces the field existing along the axis of the inductor to a level just sufficient to maintain equilibrium in the feedback loop. A zero-center, strip-chart recording instrument in the feedback circuit continuously records the magnitude and polarity of the direct current, expressed in terms of the intensity and polarity of a field which consists of the algebraic sum of the field neutralized by the current and the residual field along the axis of the inductor that is required for feedback equilibrium. Adjustments in the feedback circuit allow for sensitivity settings of 100, 500, 1000, and 2500 γ for a deflection of the recorder pen across the full width of the chart. Since the maximum range of field which the feedback loop can handle is only 2500 γ, it functions as a variometer.

By means of another but stronger direct current which also passes through the inductor winding, the field in the inductor is reduced to a level which the feedback system can accommodate. This stronger current (I_m of Fig. 1) is obtained from a stable, battery-regulated source. A three-decade resistance box interposed between the stable source and the inductor provides the means for adjusting and measuring, in terms of the field neutralized, the value of the stronger inductor current. The three-decade channels enable adjustments of the neutralization field to be made in increments of 50, 500, and 5000 γ, respectively. The field intensity represented by the decade settings and the instantaneous magnitude of the field registered on the strip chart are combined to obtain the value of the geomagnetic field intensity.

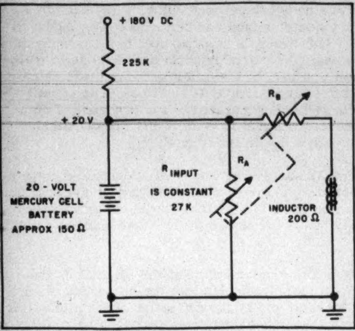


Fig. 2--Stable voltage source for the inductor bias-current control

Direct-current source for the decade box--The high degree of stability required of the d-c source has been achieved with the circuit shown in Figure 2. This circuit, based on one described by POTTER [1943], consists of a 225,000-ohm resistor connected to a parallel circuit containing a 20-volt battery in one leg and the constant 27,000-ohm load resistance of the decade box and inductor in the other. The battery comprises 15 mercury-compound cells connected in series; its internal resistance is about 150 ohms.

The circuit is energized at 180 volts from the magnetometer's regulated vacuum-tube power supply, providing approximately 95 pct of the current the decade box requires. The rest is furnished by the battery and is only about 20 microamperes, so that a battery life of about one year can be expected. Because of its low internal resistance, the battery functions as a regulator to stabilize the output voltage of the d-c source. A change of 0.5 volt in the potential supplied to the circuit by the power supply alters the output of the d-c source by only one part in 50,000. The regulation of the 180-volt supply is normally well within ±0.5 volt. Before the start of a survey flight, the output voltage of the d-c source is adjusted with the aid of a portable potentiometer constructed especially for this purpose. Prior to this adjustment, the standard cell in the portable potentiometer is standardized against a bank of cells maintained at the base of operations.

Measurement of the direction of the field with respect to the orientor--Figure 3 shows how the field-measuring inductor D is supported. The mount which supports inductor D also holds two

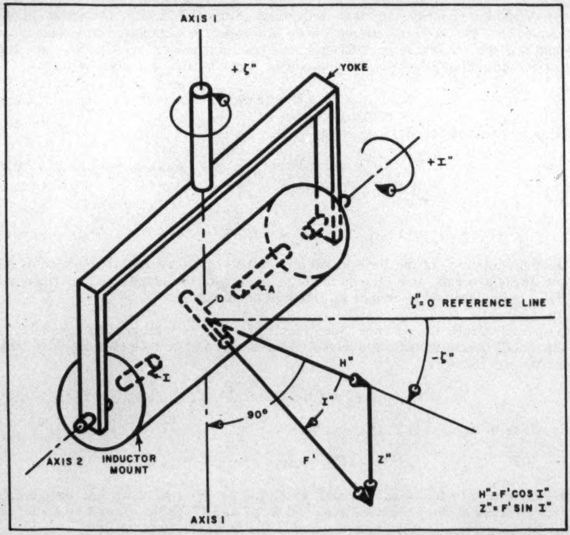


Fig. 3--Diagram of the two-axis support for the saturable inductors additional inductors A and I. The three inductors are mutually perpendicular, with inductor A aligned parallel with the long axis 2 about which the inductor mount can be turned. The mount is supported by a yoke that can be turned about axis 1. Inductor A is incorporated in a servo-system containing a motor (not shown on the diagram) that turns the assembly about axis 1 so as to maintain inductor A perpendicular to the field. Inductor I is a part of a similar servo-system which turns the inductor mount about axis 2 to keep inductor I perpendicular to the field. The signals which activate the servo-systems are the 2000-cycle voltages generated by the presence of components of the field along the axes of the orientor inductors A and I. With A and I perpendicular to the field, as shown in Figure 3, inductor D will be aligned with the field F.

In one of the two arrangements used for pendulously suspending the VAM-2A orientor, axis 1 becomes the plumb line. This arrangement is referred to as the vertical mounting or vertical suspension. In this mounting, the axis of inductor D can be turned in a horizontal plane about axis 1 and in some vertical plane about axis 2. Inductor D, then, is gimbaled in the same manner as is the barrel of an anti-aircraft gun.

Greek letter ζ'' and Roman letter I'' identify the angular orientations of the inductor D about axes 1 and 2, respectively. The double-primed superscript (″) denotes that the magnitude of an angle has been affected by the magnetic field of the aircraft and by the deflection of the plumb line by Coriolis force. A single-primed superscript (′) is associated with items that have been affected by aircraft magnetism alone.

The position of the yoke for $\zeta'' = 0$ is determined mechanically by causing a cone-pointed pin, which slides in a close-fitting hole in the frame of the orientor, to be seated in a V groove located in one arm of the yoke. When the magnetometer is installed in the aircraft, the orientor frame is so positioned that angle ζ'' will be essentially the magnetic heading of the aircraft. Angle I'' is zero when the field to which the orientor is subjected is perpendicular to axis 1. Except for the effects of Coriolis force and of the field of the aircraft, angle I'' is the angle of dip of the Earth's field, provided the accelerations of the aircraft are zero. The method for minimizing the effects of an aircraft's normal flight oscillations on the accuracy of the measurements is discussed in a later section.

In order to state the equations for the components of the field vector at this stage of the paper, it will be assumed that the angular data have been processed to eliminate the influences of flight oscillations and that the necessary corrections have been made for Coriolis force and for the aircraft's magnetic field. Thus, the vertical component Z of the field will be given by

$$Z = F \sin I \quad \ldots\ldots\ldots\ldots \quad (1)$$

the horizontal component H will be

$$H = F \cos I \quad \ldots\ldots\ldots\ldots \quad (2)$$

and the angle of declination D will be

$$D = TH_m - \zeta \quad \ldots\ldots\ldots\ldots \quad (3)$$

where F is the total intensity of the field which is obtained by correcting the measured magnitude F' for the field of the aircraft, and TH_m is the true heading of the reference line from which ζ'' is measured. TH_m is determined by means of celestial observations.

Owing to space limitations, the correction factors for the deflection of the pendular orientor by Coriolis force will be stated but not derived. The factor $\Delta\zeta''_c$ to be added algebraically to ζ'' to correct it for Coriolis force is

$$\Delta\zeta''_c = \epsilon \tan I'' \cos \zeta'' \quad \ldots\ldots\ldots\ldots \quad (4)$$

and the factor $\Delta I''$ to be applied to I'' is given by

$$\Delta I'' = -\epsilon \sin \zeta'' \quad \ldots\ldots\ldots\ldots \quad (5)$$

where ϵ is the angle in minutes of arc through which the pendular orientor has been deflected by Coriolis force. Because of the polarities assigned to ζ'' and I'', angle ϵ must be considered to be negative in the Northern Hemisphere and positive in the Southern Hemisphere.

Mechanical means, however, are usually used to neutralize the deflection of the pendular orientor by Coriolis force. A hand-operated mechanism attached to the orientor has a weight which can be shifted across a scale calibrated in minutes of arc to create a torque on the orientor equal but opposite to that produced by Coriolis force.

A mathematical method for correcting the survey results for the field of the aircraft has been described [HURWITZ, 1953].

Orientor mechanism--Figure 4 is a simplified diagram of the orientor mechanism suspended vertically in its supporting frame. The yoke is connected by means of a tubular shaft and reduction gearing to the servomotor labeled 'azimuth.' This motor turns the assembly about axis 1. Also geared to the tube and located opposite the servomotor is the azimuth synchro transmitter, which is the sensing device for measuring angle ζ''.

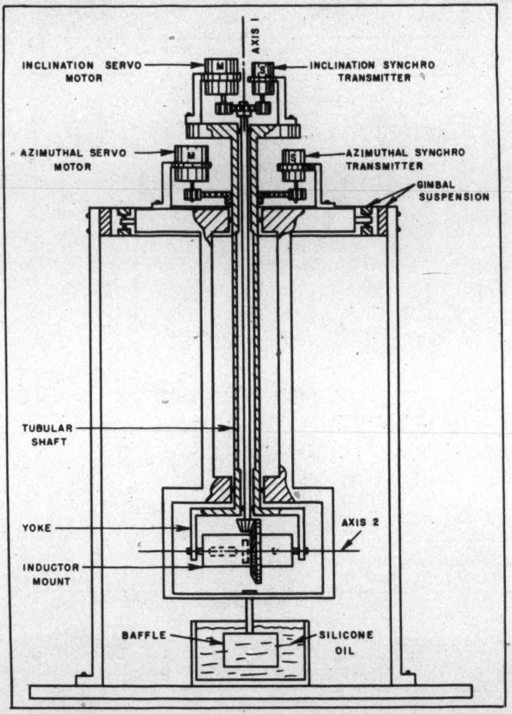

AXIS 1
INCLINATION SERVO MOTOR
M
S
INCLINATION SYNCHRO TRANSMITTER
AZIMUTHAL SERVO MOTOR
M
S
AZIMUTHAL SYNCHRO TRANSMITTER
GIMBAL SUSPENSION
TUBULAR SHAFT
YOKE
AXIS 2
INDUCTOR MOUNT
BAFFLE
SILICONE OIL

Fig. 4--Diagram of the orientor in its vertical suspension assembly

A platform connected to the upper end of the tube and turning with it supports another servomotor and another synchro transmitter each of which is labeled 'inclination.' The inclination motor, through reduction gearing and a shaft running through the tube, drives the inductor mount about axis 2. The inclination synchro transmitter is used in measuring angle I''. Although not so indicated by the diagram, the rotors of the azimuth and inclination synchro transmitters are geared to turn with the detector inductor about axes 1 and 2, respectively, in one-to-one ratios. Figure 5 is a photograph of a completed orientor equipped with a compensator for Coriolis force.

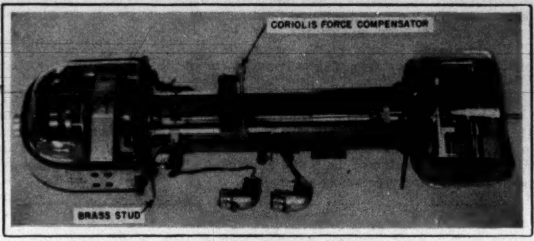

CORIOLIS FORCE COMPENSATOR
BRASS STUD

Fig. 5--Orientor mechanism

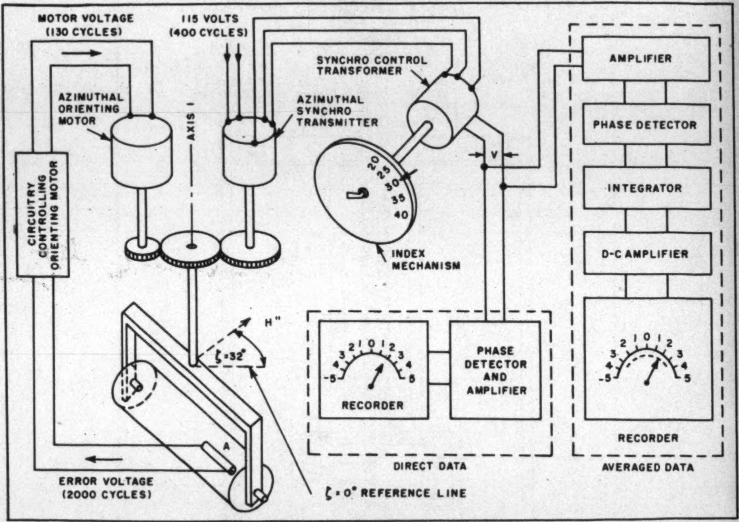

MOTOR VOLTAGE
(130 CYCLES)
115 VOLTS
(400 CYCLES)
SYNCHRO CONTROL
TRANSFORMER
AZIMUTHAL
ORIENTING
MOTOR
AXIS I
AZIMUTHAL
SYNCHRO
TRANSMITTER
CIRCUITRY
CONTROLLING
ORIENTING MOTOR
20
25
30
35
40
INDEX
MECHANISM
V
AMPLIFIER
PHASE DETECTOR
INTEGRATOR
D-C AMPLIFIER
H"
ζ=32°
-5 4 3 2 1 0 1 2 3 4 5
RECORDER
PHASE
DETECTOR
AND
AMPLIFIER
-5 4 3 2 1 0 1 2 3 4 5
RECORDER
A
DIRECT DATA
AVERAGED DATA
ERROR VOLTAGE
(2000 CYCLES)
ζ=0° REFERENCE LINE

Fig. 6--Diagram of angle-measuring circuits

Angle-measuring system--Angles ζ'' and I'' are each measured in individual circuits of the type shown in block form by Figure 6. This figure depicts in particular the arrangement for measuring angle ζ''. The azimuth synchro transmitter is shown geared through an intermediate tube to the yoke of the orientor, and is also shown wired in the usual way to a synchro control transformer mounted in an index mechanism.

The index mechanism is used by the magnetometer operator to turn the rotor of the transformer manually through angles which are integral multiples of five degrees. A dial, graduated through 360° in five-degree increments, indicates the angle through which the rotor has been turned from its 'zero' position. Figure 7 is a photographic view of the index mechanism without its dial.

Referring to Figure 6 again, the rotor winding of the transmitter is excited at 115 volts, 400 cps. Unless the rotors of the transmitter and transformer happen to be turned through identical

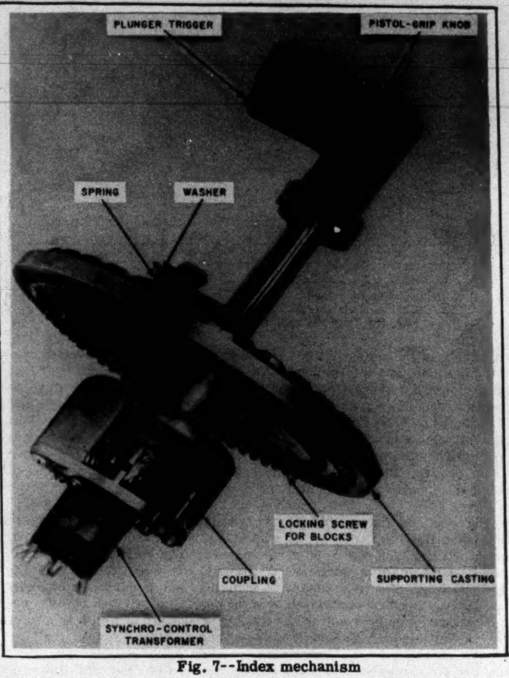


Fig. 7--Index mechanism

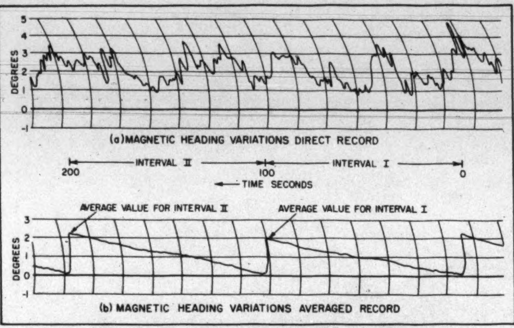
angles from their respective zero positions, a 400-cycle voltage will appear across the rotor winding of the control transformer. This voltage will be given by

$$v = k \sin (\phi_1 - \phi_2)$$

where ϕ_1 and ϕ_2 are the angles through which the rotors of the transmitter and transformer, respectively, have been turned, and k is a constant.

Voltage v is amplified, phase-detected, and recorded on a zero-center, strip-chart recording milliammeter. The constants of the circuit are adjusted so that the instrument will register $\phi_1 - \phi_2$ in degrees for angular differences as large as $\pm 5°$. When $\phi_1 - \phi_2$ exceeds that range, the operator turns the control transformer rotor in steps of five degrees until the recorder pen is again on scale. The angle to be measured will be the algebraic sum of the angle indicated by the dial of the index mechanism and that registered on the strip chart. Angle ζ'' in Figure 6 is 32°, of which 30° are shown by the index mechanism and two degrees are registered on the recorder.

Figure 8a shows a record of variations in ζ'' obtained in flight using a P2V aircraft. Only a small part of the short-period variations recorded can be attributed to changes in aircraft heading. The bulk of the excursions shown can be ascribed to the magnified servo-action that was required on account of the large ambient angle of dip to follow the small oscillations of the pendular mechanism.



(a) MAGNETIC HEADING VARIATIONS DIRECT RECORD

(b) MAGNETIC HEADING VARIATIONS AVERAGED RECORD

Fig. 8--Typical magnetic heading variations

The adverse effects of these oscillations of the orientor, which are caused by the aircraft's roll, pitch, and yaw motions, are minimized by averaging the angular data over fixed intervals of flight. The interval employed approximates the time required for the aircraft to complete two phugoid (pitch) oscillations. The reasons for the selection of this interval are stated in a previous paper [SCHONSTEDT and IRONS, 1953]. The phugoid of a P2V has a period of about 50 sec, so the angular measurements obtained with the VAM-2A in this type of aircraft are averaged over intervals of 100 sec each. The data obtained with the VAM-1A magnetometer are averaged by manually scaling the recorder charts. Electronic circuits of the VAM-2A system perform the averaging automatically and continuously during flight.

Reverting to Figure 6, the output voltage v is fed also to a portion of the angle-measuring circuit, enclosed by dashed lines in the diagram, where it is amplified, phase-detected, and converted into a direct current which charges a bank of condensers. The voltage developed across the condensers is allowed to build up for a period of 100 sec. At the end of this period the condensers are rapidly discharged by means of a relay-operated shorting switch and a new charging cycle begins. The length of the charging cycle is controlled by a process timer driven by a 60-cycle synchronous motor. The motor is energized by a power supply, the frequency of which is precisely regulated by a temperature-compensated tuning fork.

The instantaneous voltage existing across the condensers is connected to the input of a single-stage, direct-coupled amplifier which drives the pen of another strip-chart recorder. The gain is adjusted so that the value recorded on the strip chart at the end of an integration period will be the average of $\phi_1 - \phi_2$ for the period. The averaging and direct-recording circuits operate independently so that either or both may be used at any time.

The record shown in Figure 8b was produced simultaneously with that in Figure 8a. The magnitude of ζ'' recorded at the end of each cycle in Figure 8b is the average value of ζ'' recorded in Figure 8a for each corresponding 100-sec interval. Angle I'' is treated in a similar manner. The value recorded at the end of a cycle is combined with the magnitude shown by the dial of the associated index mechanism to obtain the total angle. Angles ζ'' and I'' so obtained are used to compute the field vector for the position over the surface of the Earth occupied by the aircraft at the instant represented by the midpoint of the 100-sec interval.

The averaging of the angular data will introduce a small error when the measurement is made over a path where the spatial variation of the field is nonlinear (an area containing magnetic anomalies). This error is minimized by using the total intensity recorded at the midpoint rather than its average for the interval.

Calibration of the angle-measuring systems--Thus far in this presentation it has been assumed that voltage v will be zero when ϕ_1 is equal to ϕ_2. Because of unavoidable imperfections in the construction of the synchro units and critical mechanical parts of the orientor, this is not true to the degree of accuracy to which it is desirable to measure ζ'' and I''. In order to improve the accuracy of the angular measurements through the process of calibration, the index mechanism has been constructed with adjustable detents.

The calibration is performed with the use of an auto-collimator and precision angle blocks which make it possible to turn the inductor mount about axis 1 or 2 in steps which are precise integral multiples of five degrees. While the inductor mount is oriented at each of such angles, the appropriate detent block in the associated index mechanism is adjusted and fixed at a position at which the voltage output of the control transformer is zero. Each angle-measuring circuit is precisely calibrated at points spaced five degrees apart throughout its 360° range. As a result, the portion of the total angle shown by the index mechanism is measured very accurately and the remainder, the recorded portion, will be subject to some error of tolerable magnitude. The error in the recorded portion of the angle is kept to a minimum by indexing the rotor control transformer through five degrees when the average magnitude of the angle exceeds ±3°. The magnetometer's precision of measurement has been enhanced by using synchros which have been selected for high accuracy from production runs of standard units.

Measurement of the relative bearing of the aircraft--The heading of the aircraft relative to a celestial body is determined with a Kollsman periscopic sextant which has been modified for obtaining accurate recorded measurements of azimuth angles. The unmodified sextant consists of a small periscope which has a calibrated, adjustable optical system for determining the altitude of a celestial body. The tubular portion of the periscope fits into and is secured to a three-axis gimbal mount bolted to the roof of the fuselage. The upper end of the tube projects beyond the skin of the aircraft, where an adjustable prism within the tube has an essentially unobstructed view of the

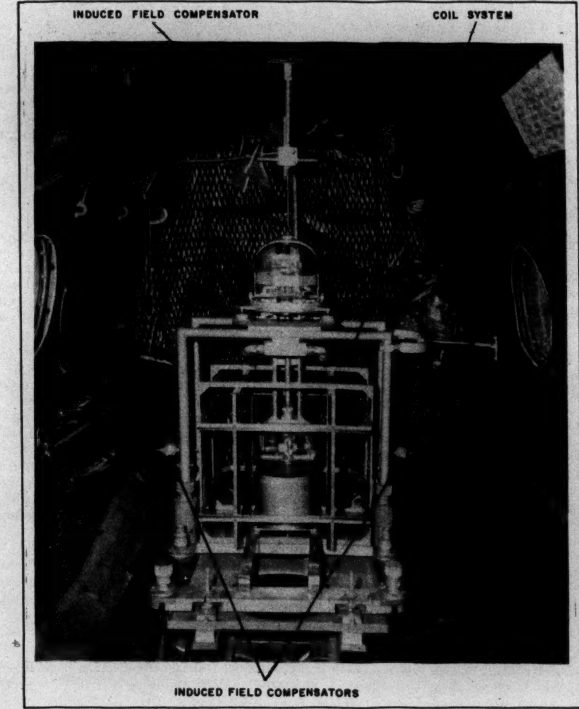


Fig. 9--Orientor assembly installed in P2V aircraft sky. The two horizontal axes of the gimbals permit the sextant to be properly leveled, and the third allows the sextant to be turned to any angle in azimuth.

A synchro transmitter has been secured to the gimbal mount and geared so that its rotor turns in azimuth in a one-to-one ratio with the periscope. The transmitter is incorporated in an angle-measuring circuit with which both the direct and averaged variations of relative bearing are recorded.

The operator of the instrument collimates on a star or the Sun for a period of about two minutes out of every five. During this two-minute period, the relative bearing angle is also automatically averaged over the same 100-sec interval as are the other magnetometer angles. Since only one value of relative bearing, from which the true heading of the magnetometer is computed, is obtained for each five minutes of flight, it has been the practice to compute the components of the field for points spaced by the distance covered in five minutes.

The position of the aircraft can be determined quite accurately in regions in which there is good Loran coverage or where visual navigation can be used. However, much remains to be desired when position must be determined by celestial methods ordinarily used in air navigation. Some progress is being made on this problem by various Government agencies.

General description of the components--Figure 9 shows the orientor in its suspension assembly in the interior of the aircraft. The outer ring of the gimbals which freely support the mechanism rests on vibration insulators, which in turn are secured to a plastic ring that is mounted on a tubular frame. The tubes of one U-shaped portion of the frame have internal cables terminating at their lower ends in plugs which engage sockets on the wooden base. The upper ends of the cables end in sockets which connect to the plugs on the orientor leads. The triaxial Helmholtz coils are used to compensate for the permanent magnetic field of the aircraft at the inductors. The pendulous orientor is damped by means of a baffle connected to its lower end. The baffle is immersed in a viscous silicone oil held by the cylindrical pot. The unit is normally covered with a plastic tent to exclude dust and to prevent air currents from the aircraft's heater from impinging on the pendular mechanism. The sway bar on the right anchors the suspension frame to the side of the aircraft to reduce oscillations of the assembly about the vibration mounts of a subbase to which the assembly is secured. A part of the permeable masses used for compensating for the induction field of the aircraft at the inductors are shown also.

Figure 10 is a photograph of the modified periscopic sextant in operation. A supporting leg has been added to the periscope to minimize operator's fatigue. The lower end of the leg has a spring-loaded pin which bears against a plate on the post supporting the operator's chair. The design permits the leg to be shifted over the surface of the plate for leveling the sextant and allows the sextant to be turned in azimuth as required. There is enough friction between the pin and the plate so that little or no hand support is required to maintain the sextant in its leveled position.

Figure 11 is a photograph of most of the components of the VAM-2A. Not mentioned previously but included in the photograph is a directional gyroscope, with which variations in the heading of the aircraft are continuously recorded. A synchro transmitter has been coupled to the cardan axis of the gyro and incorporated in an angle-measuring circuit of the type described previously. The variations in heading, however, are not averaged. The gyro record serves to show when the aircraft has made turns of sufficient magnitude to affect seriously the vertical-reference accuracy of the pendular orientor.

Each of the two boxes with the large graduated dials on the right-hand side of Figure 11 contains two index mechanisms. One box has the index mechanisms for the ζ'' and I'' angles, and the other holds the mechanisms for the relative bearing and aircraft heading angles. The control panel of the system is just above the two boxes.

Eight Esterline Angus strip-chart recording instruments are included in the installation. Four record the direct and averaged variations of ζ'' and I'', two record the direct and averaged variations in relative bearing of the aircraft, one shows the variation in the total field intensity, and the remaining one shows the variation in aircraft heading. The recorders are driven by 60-cycle synchronous motors energized by the output of the highly-accurate 60-cycle power supply which also drives two process timers. One timer, mentioned previously, controls the integration period of the averaging circuits; and the other actuates chronograph pens on the recorders to mark the edges of the strip charts once every five minutes. The power supply is not shown in the photograph.

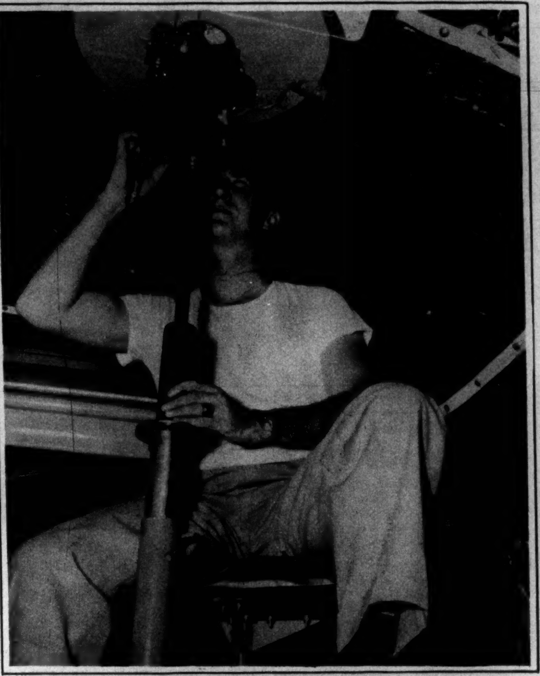
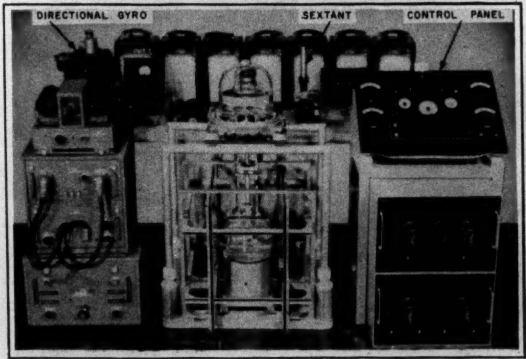


Fig. 10--Modified periscopic sextant in operation



DIRECTIONAL GYRO
SEXTANT
CONTROL PANEL

Fig. 11--VAM-2A components

The P2V aircraft in which the Hydrographic Office has installed the VAM-2A is shown in Figure 12. The locations of the various portions of the magnetometer installation are indicated by the arrows and captions. Figure 13 shows part of the control and recording equipment. The recording instruments are faced in opposite directions so that the strong fields from their magnets will largely cancel each other at the magnetometer orientor.

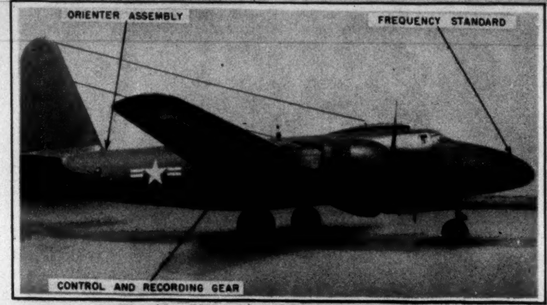

ORIENTER ASSEMBLY
FREQUENCY STANDARD
CONTROL AND RECORDING GEAR

Fig. 12--P2V equipped for magnetic surveys

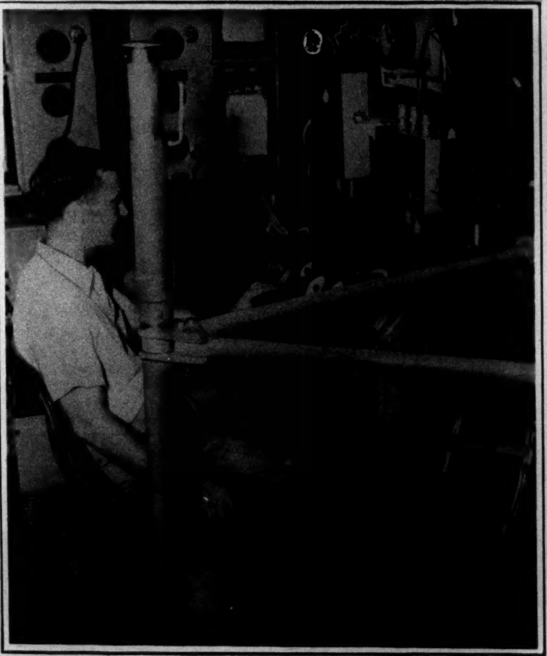


Fig. 13--Control and recording equipment in the P2V

Horizontal suspension--In the polar and subpolar areas of the Earth, where the direction of the field approaches parallelism with axis 1, the variations of ζ'' arising from aircraft pitch and roll become excessive. This is related to the behavior of an aircraft compass in those regions. When surveys are to be conducted in areas in which the angle of dip exceeds approximately 80 to 85°, depending upon the magnetic heading to be followed, the orientor should be suspended as shown in Figure 14 so that axis 1 becomes horizontal. This horizontal suspension of the orientor is suitable for operations over the entire surface of the Earth except for an equatorial band where the angle of dip is within about ±10°. Here axis 1 may again become too closely aligned with the field. (The earlier VAM-1A was designed for moderate and high latitudes and could not be used where the dip was less than 45°.)

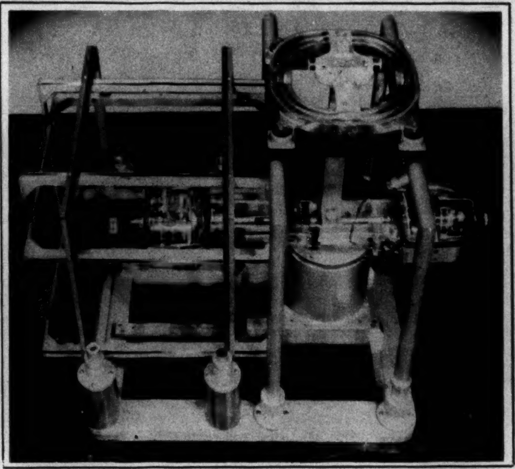


Fig. 14--Horizontal suspension of the VAM-2A orientor

In changing to the horizontal suspension, the tubular frame which supports the orientor is shifted to the lower mounting couplings of the base. Two of the couplings are wired in parallel with two of those of the raised portion of the base. The T-shaped suspension bar has been added to connect the orientor to the suspension gimbals. The pot of oil is also shifted so that it is directly under the axis of the suspension bar. A somewhat larger baffle is used in order to achieve approximately the same amount of damping that exists for the vertical suspension. The orientor is arranged in the aircraft with the servomotor end forward.

Angles of the horizontal suspension--The magnetic heading of the aircraft and the angle of dip of the field are not obtained directly with the horizontal mounting, so θ'' and ψ' are used to denote the angular displacements about axes 1 and 2, respectively. Angle ψ' is not affected by Coriolis force, so it has only a single-primed superscript.

No electric-circuit modifications are made in changing to the horizontal mounting. The dial of the index mechanism used to measure I'' can be turned over to obtain graduations from zero through 355° so that ψ' may be stated in terms of only positive angles.

As shown in Figure 15, the reference line from which angle ζ'' was measured will now be vertical and directed downward from inductor D. Inductor D will now turn about axis 1 in a vertical plane. When viewed from the servomotor end of the orientor towards the inductor end, angle θ'' will be positive for angles measured in the counterclockwise direction from the reference line. This is the same direction the yoke turns with respect to the orientor frame for positive values of ζ''.

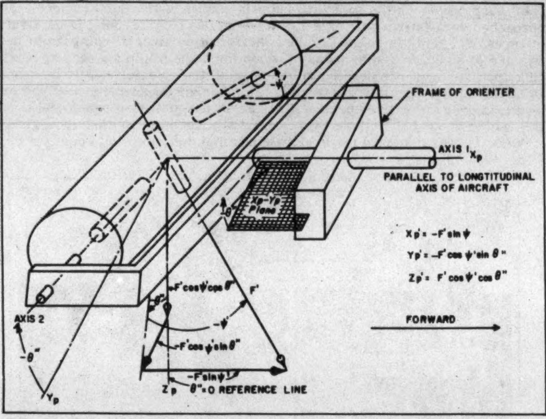

FRAME OF ORIENTER
AXIS 1 X_p
PARALLEL TO LONGTITUDINAL AXIS OF AIRCRAFT
X_p-Y_p Plane
θ''
$X_p' = -F' \sin \psi'$
$Y_p' = -F' \cos \psi' \sin \theta''$
$Z_p' = F' \cos \psi' \cos \theta''$
FORWARD
F'
$-F' \cos \psi' \cos \theta''$
$-\theta''$
$-\psi'$
$-F' \cos \psi' \sin \theta''$
$-F' \sin \psi'$
Z_p
$\theta'' = 0$ REFERENCE LINE
AXIS 2
$-\theta''$
Y_p
ψ'

Fig. 15--Diagram of the inductor assembly for the horizontal suspension

As with I", angle ψ' will be zero when the field is perpendicular to axis 1. Angle I" was positive when the vertical component of the field was directed downward, in which case the component of the field along axis 1 was in the direction from the servomotors toward the inductors. Similarily, ψ' will be positive (or lie in the first quadrant of the plane in which it is measured) when the component of the field along axis 1 is in the direction from the servomotors toward the inductors. When this component of field is in the reverse direction, ψ' will be negative (or lie in the fourth quadrant if ψ' is stated only in terms of positive angles). Because of the electromechanics of the orientor, ψ' is confined to the first and fourth quadrants of the plane in which it is measured.

When the horizontal suspension is used, it is convenient to express the field vector measured with respect to the orientor frame in terms of rectangular components. The coordinate system associated with the orientor frame shown in Figure 15 has x_p coincident with axis 1, z_p coincident with the reference line from which θ'' is measured and y_p perpendicular to x_p and z_p. Axis 2 will be coincident with y_p when θ'' is zero.

Figure 15 shows the inductor mount turned about axes 1 and 2 through large magnitudes of θ'' and ψ'. In order to make the diagram appear less cumbersome, θ'' and ψ' are labeled in terms of their negative equivalents. The projection of the field F′ along the coordinate axes will yield

$$X_p' = -F' \sin \psi' \quad \ldots\ldots\ldots\ldots (6)$$

$$Y_p' = -F' \cos \psi' \sin \theta'' \quad \ldots\ldots\ldots\ldots (7)$$

$$Z_p' = F' \cos \psi' \cos \theta'' \quad \ldots\ldots\ldots\ldots (8)$$

The coordinate system is fixed with respect to the orientor frame, so it too will be deflected by Coriolis force. A second coordinate system in which x_e, y_e, and z represent the positions of x_p, y_p, and z_p, respectively, for a condition of zero Coriolis force is shown in Figure 16. This figure depicts the situation in which the orientor has been deflected through angle ϵ by Coriolis force. Coordinates x_p and x_e are coincident since the deflection ϵ takes place in a plane perpendicular to them. A simple correction is applied to θ'' to obtain θ', and so the components measured with respect to the second coordinate system will be

$$X_e' = -F' \sin \psi' \quad \ldots\ldots\ldots\ldots (9)$$

$$Y_e' = -F' \cos \psi' \sin \theta' \quad \ldots\ldots\ldots\ldots (10)$$

$$Z' = F' \cos \psi' \cos \theta' \quad \ldots\ldots\ldots\ldots (11)$$

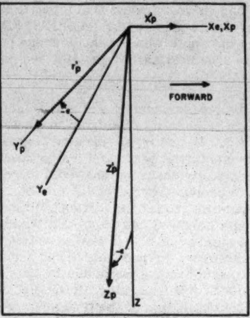


Fig. 16--Deflection of pendular coordinate system by Coriolis force

where θ' is equal to $\theta'' + \epsilon$. The correction of θ'' for Coriolis force is so simple in this case that it is more convenient to use mathematical means than to use mechanical compensation.

The correction for aircraft magnetism removes the primed superscripts from the terms of (9), (10), and (11) to give X_e, Y_e, and Z. As mentioned previously, the magnitudes of the angles and total intensity are not corrected directly but the technique reported [HURWITZ, 1953] may be employed on rectangular components stated in the form of (9), (10), and (11).

After the appropriate corrections have been made, the vector can be computed. The vertical component will be given by

$$Z = F \cos \psi \cos \theta \quad \ldots\ldots\ldots \quad (12)$$

the angle of dip will be

$$I = \text{arc sin}\, Z/F = \text{arc sin}\, (\cos \psi \cos \theta) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (13)$$

the horizontal component will be

$$H = F \cos I = F \cos \text{arc sin}\, (\cos \psi \cos \theta) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (14)$$

the magnetic heading will be

$$\zeta = -\,\text{arc tan}\, (Y_e/X_e) = -\,\text{arc tan}\, [(\cos \psi \cos \theta)/\sin \psi] \quad \ldots\ldots\ldots\ldots \quad (15)$$

and the angle of declination may be obtained from (3).

Sources of error in measurements made with the VAM-2A--The magnetic measurements made with the magnetometer are subject to errors arising from three major sources, namely, (a) aircraft magnetism, (b) the effects of aircraft accelerations on the accuracy of the vertical reference, and (c) instrument errors. The magnitude and sign of errors due to aircraft magnetism depend upon the heading of the plane and the ambient values of F and I. The errors are also slightly time-dependent because the magnetic state of the aircraft changes slowly with time. Aircraft magnetism can be dealt with in two general ways. One method is to conduct a study to determine the character of the magnetic field of the aircraft and, from the results of this study, determine the correction factors to be applied to the survey data obtained with the magnetometer [HURWITZ, 1953]. Another method is to use a system of compensating devices to neutralize the magnetic field of the aircraft at the magnetometer. The latter method was emphasized for the installation of the VAM-2A in the P2V. Some of the components of the compensation system of the aircraft are shown in Figure 9.

During flights at Key West, Florida, compensation adjustments were made to the point where the variations in F and I with heading which were due to aircraft magnetism were reduced to maxima of $\pm 4\gamma$ and ± 0.5 min of arc, respectively. The observed values of D, the declination angle, are directly affected by the accuracy to which the true heading of the aircraft is ascertained, so no precise measurement of the variations of D due to aircraft magnetism were possible. However, from the variations of F and I at Key West, where the angle of dip is about 58°, an accompanying variation in D arising from aircraft magnetism alone of less than ± 1 min of arc would be expected.

On the day following the completion of the compensation flights at Key West, the aircraft was flown northward to an area having a dip angle of about 71° which was located near Ocean City, Maryland. While employing the same compensation settings used at Key West, a check made over this area yielded maximum variations with heading of F, I, and D of approximately $\pm 10\gamma$, ± 1 min of arc, and ± 2 min of arc, respectively. This slight deterioration in the compensation was probably due to changes in the character of the aircraft's field with time and with latitude. The latitude effect in general should be small and of no practical consequence, especially when a survey starts and terminates at the same point. Various tests made after those mentioned above indicate that the necessary checks required to keep the net errors in F and I due to aircraft magnetism to less than $\pm 15\gamma$ and ± 1.5 min of arc, respectively, would not be too numerous to be carried out as a part of a practical survey program.

The character of inaccuracies which affect the measured values of I and D arising from errors in the magnetometer's vertical reference has been discussed in a prior paper [SCHONSTEDT and IRONS, 1953]. The vertical-reference error considered is the angle between the average position of the plumb line of the orientor and the average position of true vertical for the 100-sec period over which the angular data are averaged.

The extent to which vertical-reference errors affect the measurements of I and D is determined by making repeated flights over a given course that is essentially free from magnetic anomalies, and noting the spread in the values of I and D observed. At Key West repeated flights in smooth air at an altitude of 10,000 ft were made over north-south and east-west tracks, each of which was about 25 miles long. An analysis of the 24 values of dip observed showed a standard deviation of 1.8 min of arc. This deviation corresponds to a probable error of 1.2 min of arc, attributed to a net average displacement of the vertical reference from true vertical. Since the determination of declination required manual collimation on a celestial body to obtain true heading, practical limitations of human endurance precluded a large number of direct determinations of the probable error in D arising from aircraft accelerations. However, the probable error ascertained for I would indicate an accompanying probable error in magnetic heading angle due to aircraft accelerations of 2.0 min of arc for the Key West tests. The error in D from aircraft accelerations would be slightly larger than two minutes of arc since the determination of the true heading of the aircraft also involves a gravity-controlled vertical reference.

The errors produced by the instrument itself are due to small inaccuracies in the calibration, inaccuracies in the graphic recorders, nonlinearities in components of the circuits, and effects arising from temperature and magnetic hysteresis. The probable errors from these sources are two minutes in the measurement of dip, magnetic heading, and relative bearing; and five gammas in the measurement of F. The five-gamma estimate is based on the assumption that the field used as a reference for original calibration of the magnetometer does not represent a source of significant error. Drift in the measured value of F from factors other than temperature is about one gamma in 12 hr. Variations in F with temperature occur at a rate of about $0.5\gamma/^\circ$ C.

The combination of the three general types of errors covered in the foregoing discussion indicates that the over-all probable error in F and I are 16γ and three minutes of arc, respectively. The total error in D is a function of the same three main sources of error, but it is also dependant upon the ambient angle of dip and the elevation angle of the celestial body used as a directional reference. For an angle of dip of 60° and an elevation angle of 20° for a celestial body, the probable error in declination is believed to be approximately five minutes of arc.

The comparison of airborne measurements with ground values--The value of F indicated by the magnetometer can be easily compared with that determined at a magnetic observatory by measuring F on a low-altitude flight over the observatory. In a flight over the Magnetic Observatory at Cheltenham, Maryland, the magnitude of F indicated by the magnetometer, after correction for drift in the reference standard cell, was within four gammas of the Observatory's value.

A comparison of the magnitudes of D and I indicated by the magnetometer with ground values is more difficult than the F comparisons. The airborne measurements usually must be made at normal survey flight altitude (approximately 10,000 ft) to obtain smooth flight conditions. Also, the measurements indicated by the magnetometer are the average values of D and I over 100-sec intervals which correspond to approximately six miles of flight. Unless the measurements are made in an area where the gradients in D and I are small and uniform, it is quite difficult to determine from ground measurements made at a single location the magnitudes of D and I that correspond to the airborne measurements. The problem is further complicated by difficulties encountered in piloting the plane over the desired course without making any turns during the 100-sec interval when the measurements are made.

Despite these difficulties, two quite accurate measurements of the angle of dip were made during flights over the Cheltenham Magnetic Observatory. One measurement was within four minutes of the Observatory value, and the other was the same as the Observatory value. For eight airborne measurements of I over Key West, the average deviation from the value of I for a nearby ground station was three minutes of arc.

The average error for 16 values of declination angle observed at Key West and Washington, D. C., was approximately five minutes.

Acknowledgment--The valuable cooperation and assistance of the following organizations in the development, calibration, and testing of the magnetometer is gratefully acknowledged. The

Ford Instrument Company participated in the design of the gears and gear mounts of the orientor. The Hydrographic Office assisted in the calibration of the magnetometer, furnished apparatus incorporated in the instrument, and made available for this report its test results and photographs of its installation. The U. S. Coast and Geodetic Survey assisted in the calibration of the magnetometer and provided the use of the facilities at its Magnetic Observatory at Cheltenham, Maryland. The development of the magnetometer was sponsored in its early phase by the Office of Naval Research and was completed under sponsorship of the Hydrographic Office.

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CONCENTRATION DISTRIBUTIONS IN AEROSOL PLUMES THREE TO TWENTY-TWO MILES FROM A POINT SOURCE

W. D. Crozier and Ben K. Seely

Abstract--Analyses of particle distributions in 15 cross sections of experimental aerosol plumes, each from a point source at ground level, indicated that the horizontal distribution of particle concentration was expressed fairly well by $C = C_m \exp(-By^n)$. Here C_m, B, and n are parameters; and y is the distance from the center of the plume, measured horizontally in either direction in the plane of the cross section. The equation was applied in two ways: in one the concentration C is the average along a vertical line the height of the plume, and in the other C gives the concentrations met on the average along single horizontal passes through the plume. Meandering of the plume has an important effect in the first case; crosswise wind shear is important in both cases.

Introduction

BRAHAM, SEELY, and CROZIER [1952] have described tests made in central New Mexico in May, 1951, of a technique for tagging air parcels with an aerosol of fluorescent material and then tracing the air through the process of turbulent diffusion by means of the aerosol. Sampling equipment carried in an airplane made it possible to determine particle concentrations and distributions downwind from the tagging point.

Further tagging and tracing tests were made on the plains of eastern New Mexico in June and July of 1952. Improvements in the technique were used in these tests, and it was hoped that the wind patterns would be simpler over the plains than among the mountain ranges which characterized the locale of the 1951 tests.

Additional tagging and tracing work was done in Australia during the period July to September, 1953, in collaboration with the Commonwealth Scientific and Industrial Research Organization. This work was done over level terrain at two locations, near Dubbo, New South Wales, and near Bundaberg, Queensland, with the same method and equipment used in the 1952 tests. A representative (Seely) of the New Mexico Institute of Mining and Technology participated in the Australian tests.

This paper presents analyses of the better data on the distribution of particle concentration in cross sections of the aerosol 'plumes' obtained in all three of the above series of tests and makes comparisons with theoretical distributions. The 1952 data are the most complete and systematic; consequently, they are treated first.

Method and equipment

All the tests were made with an aerosol of fluorescent ZnS pigment (no. 2210 of the New Jersey Zinc Company) dispersed from a stationary point at ground level. The 1951 dispersals were made at the rate of about 3×10^{10} particles/sec by means of a smoke generator or by a 'dry duster,' both described by BRAHAM, SEELY, and CROZIER [1952]. The 1952 dispersals were by the duster at about 8×10^{10} particles/sec, while the 1953 dispersals, also by the duster, were at rates ranging from 3×10^{10} to about 3.6×10^{11} particles/sec.

The air was sampled by using a continuously operating impactor mounted in an airplane. The impactor equipment used in the 1952 and 1953 tests was an improved form of that used in 1951 and described by BRAHAM, SEELY, and CROZIER [1952]. The improvements included: (a) provision of a built-in microscope and ultraviolet illuminator, so that the arrival of tagging particles could be seen during the sampling flights; (b) substitution of a 0.050-inch slit for the 0.125-inch circular nozzle orifice; (c) an increase in speed of the adhesive-coated strip receiving the particle collection from 0.12 to 0.32 in/min; (d) provision for making timing marks on the collecting strip; and (e) increases in the pressure head on the nozzle, which increased the rate of processing air from 35 to 60 or 70 ℓ/min. Changes (b) and (c) increased the resolution of the system by a factor of about 7.

Experimental data of 1952

__Particle distributions__--Particle-distribution data from five aerosol plume cross sections explored in 1952 seemed to be sufficiently systematic and complete for the kind of analysis applied

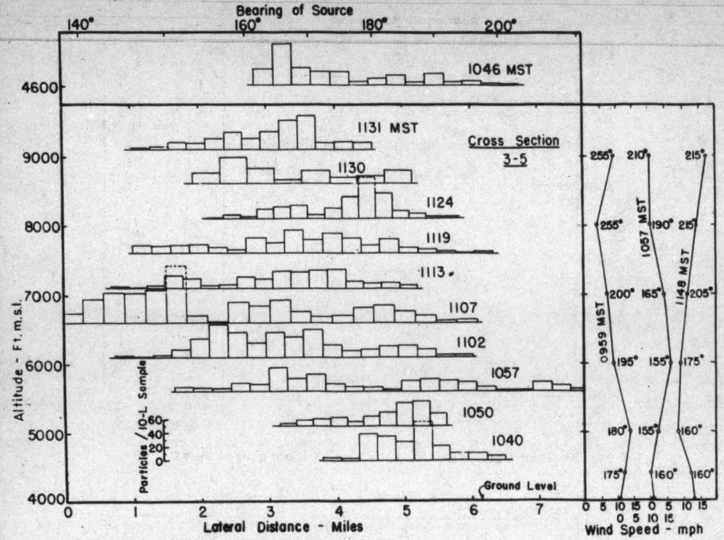

Fig. 1--Plume cross section five miles from source, June 27, 1952

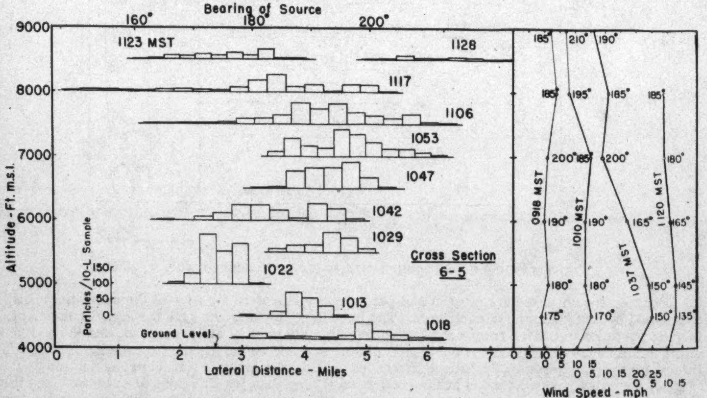

Fig. 2--Plume cross section five miles from source, June 30, 1952 in this paper. The cross sections are designated by the symbols 2-4.5, 3-5, 6-5, 18-7, and 15-9, the numbers following the hyphens giving the distances in miles from the dispersal point to the section. Exploration of each section included six to 12 horizontal passes in a plane approximately normal to the plume axis at altitudes ranging from near ground level to a level above the top of the plume.

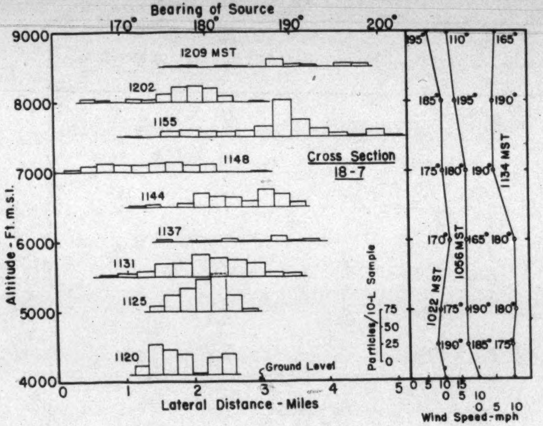

Fig. 3--Plume cross section seven miles from source July 11, 1952

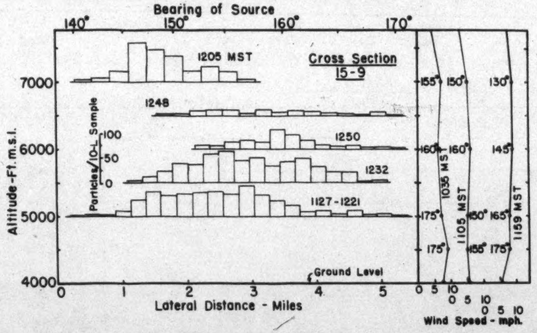

Fig. 4--Plume cross section nine miles from source, July 9, 1952

Figures 1-4 show the distributions of particle concentration for four of the cross sections, expressed by a histogram for each pass. The heights of the columns give the actual number of tagging particles collected from consecutive ten-liter volumes of air processed, and the widths of the columns correspond to the horizontal distances covered during the processing of each ten-liter volume. The zeros of the lateral distances are located arbitrarily. In cross section 3-5 (Fig. 1), an extra pass was made at the 4600-ft level, and data for this pass are shown at the top of the figure. In each cross section, the top of the plume was not more than 500 ft above the level of the highest pass shown in each of Figures 1-4. (No particles were found on extra passes made at 500 ft above the highest shown.)

The time of day for each pass is shown for correlation with the wind profiles at the right in Figures 1-4. Cross section 2-4.5 is omitted from this group because of uncertainties in the position of the airplane while making the passes.

Meteorological observations--The tests were made primarily for the purpose of evaluating the tagging and tracing technique; and, while some effort was made to obtain meteorological data, these are not as complete as would be desirable.

The wind profiles shown in Figures 1-4 were obtained by pilot-balloon observations made from the dispersal site during the dispersals. They are subject to the usual uncertainty accompanying such observations in turbulent air.

Estimates of gustiness in the horizontal wind were made by a method analogous to that of HEWSON and GILL [1944]. A recording three-cup anemometer was set up 13 ft above ground near the dispersal point. The anemometer records were traced with a ratchet device that totalized all the positive velocity fluctuations (greater than 0.4 mph) in a given period; the average gust intensity was obtained by dividing this total by the number of positive fluctuations in the period. The time constant for the anemometer assembly was 3.5 sec. The anemometer was not operating in the first two tests, but the results for the other three are shown in Table 1 along with other data.

Table 1--Wind data (1952 tests)

Cross section	Date flown	Observation period	Mean wind speed 13 ft above ground	Number of gusts per half hour	Average gust intensity
		h m - h m	mph		mph
2-4.5	June 26	10 45 - 11 15	12	....	....
3-5	June 27	10 30 - 11 00	11.5	....	....
6-5	June 30	10 00 - 10 30	9	42	2.9
6-5	June 30	11 00 - 11 30	11.5	55	3.0
18-7	July 11	10 00 - 10 30	10	51	2.4
18-7	July 11	11 00 - 11 30	11	51	3.3
15-9	July 9	10 00 - 10 30	7.5	34	2.4
15-9	July 9	11 00 - 11 30	5.5	24	2.0

Lapse rates aloft were determined from frequent readings of the free-air thermometer on the airplane. Within the probable error of the instrument, the lapse rates were always dry adiabatic in the interval between 5000 and 7500 ft msl (1000-3500 ft above ground level). Sometimes there was a tendency toward weak stability above the 7500-8500 ft level. This tendency was marked especially for the 2-4.5 and 18-7 explorations, and the plume did not extend appreciably above this level in either of these tests.

Complete data on the superadiabatic lapse rates near the ground were not obtained, though an attempt was made to get a rough indication by installing thermographs and mercury thermometers in shelters 4.5 and 28.5 ft above ground near the dispersal point. The thermograph data were not reliable enough for the purpose, but readings of the mercury thermometers were significant.

During the five tests discussed, the weather was fairly typical of summer conditions for the area. The early mornings were almost windless, with few or no convective clouds. Between nine and ten o'clock a southerly breeze, with considerable turbulence, would begin. Convective clouds usually would make their appearance in the morning or early afternoon, sometimes developing into thunderstorms over distant mountains.

Fairly complete records of temperature, pressure, humidity, and cloud types and coverage were made. Table 2 summarizes the cloud data in the north quadrant traversed by the aerosol plumes and includes the temperatures at the 4.5- and 28.5-ft levels at noon.

Considering the temperatures, wind velocities, and gust data, it seems reasonable to assume that the turbulence was of the same order of intensity in the first four tests. In the fifth test the turbulence seems definitely to have been less intense than in the others.

Table 2--Cloudiness at 1000-1200 ft; temperatures at 12h00m (1952 tests)

Cross section	Types of clouds in north quadrant	Cloud coverage tenths	Temperatures		
			4.5 ft	28.5 ft	Difference
			°F	°F	°F
2-4.5	Ac - Cu 1, 2	5-8	93	...	...
3-5	Ac	8-9	87	...	...
6-5	Cu 2 - Cb, Cu 1	3-5	90.7	87.4	3.3
18-7	Ac, Cb, Cu 1	4-6	86.2	83.1	3.1
15-9	Ac	9-7	76.1	74.0	2.1

Analysis of the 1952 data

Let us assume, as suggested by the theories of SUTTON [1949] and CALDER [1952], that the 'time-mean' distribution of concentration over a given cross section of a plume from a point source is expressed by an equation of the form

$$C = M \exp(-By^n) \exp(-Dz^m) \quad \ldots\ldots \quad (1)$$

Here C is the particle concentration; and y and z are, respectively, the magnitudes of horizontal and vertical coordinates in the plane of the section. The origin is on the axis, or center line, of the plume (at ground level in our case). The parameters M, B, and D are constants for a given plume cross section in a given meteorological situation, but they vary in general with the distance of the cross section from the source and with the turbulence and wind velocity. M depends also on the strength of the source. In Sutton's theory, m and n are not regarded as parameters but are given the values $m = n = 2$. Similarly, in Calder's theory, $m = n = 1$.

Consider horizontal passes made at levels $z_1, z_2, \ldots, z_r$ in a given cross section of a plume. The mean concentration averaged over narrow vertical strips, expressed as a function of y, will be

$$\overline{C} = \left\{(M/r)\left[\exp(-Dz_1^m) + \exp(-Dz_2^m) + \ldots + \exp(-Dz_r^m)\right]\right\} \exp(-By^n) \quad \ldots\ldots \quad (2)$$

The factor in the braces is a constant in a given situation, so we may write (2) as

$$\overline{C} = \overline{C}_m \exp(-By^n) \quad \ldots\ldots \quad (3)$$

$\overline{C}_m$ being regarded as the mean concentration along the vertical axis $y = 0$.

Stating this description of the plume in a form better suited to statistical analysis, we have

$$dN = A \exp(-By^n)\, dy \quad \ldots\ldots \quad (4)$$

where dN is the total number of particles collected in all the passes as they traverse a vertical strip of width dy situated at horizontal distance y from the axis of the plume.

To compare an experimental distribution with the distribution indicated by (4), the counts were first set down in a tabular array somewhat as in Figures 1-4, except that numbers were used instead of histogram columns. The axis $y = 0$ was drawn as a vertical line through the center of gravity of all the particles counted in the cross section, and parallel lines were added on either side of it with half-mile spacings. The half-mile interval was chosen as being wide enough to minimize sampling fluctuations, while giving a sufficient number of intervals for exhibiting the form of the distribution. Next, the counts were summed in each of the half-mile vertical strips. In cases where the original sampling intervals were divided between two adjacent strips (as most of them were), the counts were divided between the strips in proportion to the part of the interval in each strip. This procedure may, of course, result in some smoothing and distortion, but it is not likely that the alternative of recounting the particle collections with the new intervals would produce a significant difference.

It was found that the counts in the half-mile vertical strips were grouped in a fairly symmetrical array about the center line in a manner strongly suggestive of (4). Figure 5 shows this distribution for cross section 18-7, which is neither the best nor the worst of the four cases.

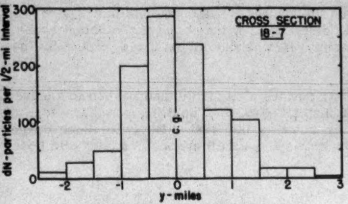

Fig. 5--Histogram of horizontal particle distribution

In view of the theoretical symmetry, which appeared to be corroborated experimentally, a second smoothing procedure was used in which the counts represented by each pair of histogram columns which were symmetrically situated with respect to the center line were averaged together and plotted as one column. The resulting histograms, shown in Figure 6, were used for comparison with the various theoretical distributions.

First, least-squares fittings to the histograms were made by using (4). The parameter n was fixed at n = 1 and n = 2, and corresponding best values were obtained for A and B. It was evident that, except for cross section 3-5, none of the fits were particularly good. Fittings then were made with n permitted to vary as well as A and B. The curves shown in Figure 6 are the results of these fittings, the parameters used being shown on each graph. These fittings were not carried to the point of obtaining true least-squares fits because of the labor involved; nevertheless, in three cases the fit was considerably better than with n fixed at 1 or 2. For 3-5, the value of n came out to be 1.98, so the fit is not significantly better than with n = 2.

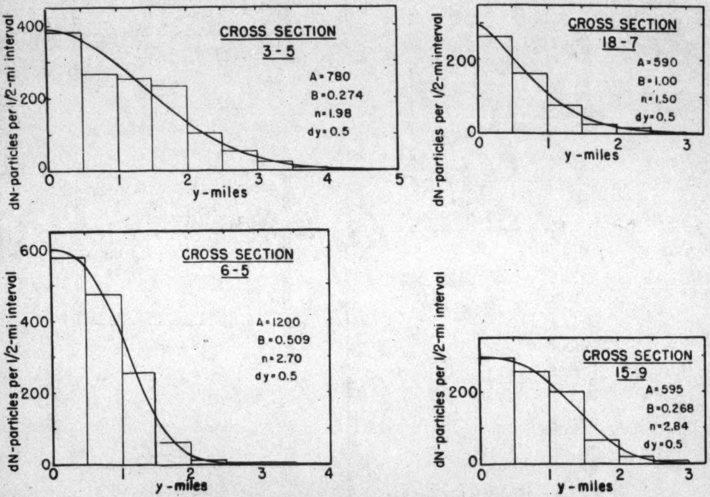

Fig. 6--Histograms of horizontal particle distributions; curves of the form $dN = A \exp(-By^n)\, dy$

In the theories of SUTTON [1949] and CALDER [1952], turbulence is regarded as superimposed on a unidirectional wind field, a condition that undoubtedly was met in the comparatively small-scale experiments used in testing the theories. In plumes extending to a height of several thousand feet, however, it is inevitable that considerable crosswise wind shear frequently will be present within the plume; this will influence greatly the horizontal distribution of particle concentration. Inspection of the wind profiles in Figures 1-4 makes it evident that crosswise wind shear must have been important in at least three of the four cases studied, 3-5, 6-5, and 15-9 (Fig. 1, 2, and 4). In the case of 18-7 (Fig. 3), the wind is fairly unidirectional; this case gives us the largest B and the smallest n. It is particularly interesting that n = 1.5 applies to this case.

In spite of the undoubted effect of wind shear on the horizontal distributions in 3-5, 6-5, and 15-9, the wind shear did not cause very pronounced distortions of the shape of the plume cross sections. This presumably is because vigorous vertical mixing was taking place throughout the height of the plumes.

Inspection of Figures 1-4 discloses that the distributions along individual passes in general are somewhat narrower than the summed distributions of Figure 6. The differences are accounted for largely by meandering of the plume during the exploration, but wind shear (with some incompleteness of vertical mixing) probably was involved, as well as small errors in timing and positioning of the data.

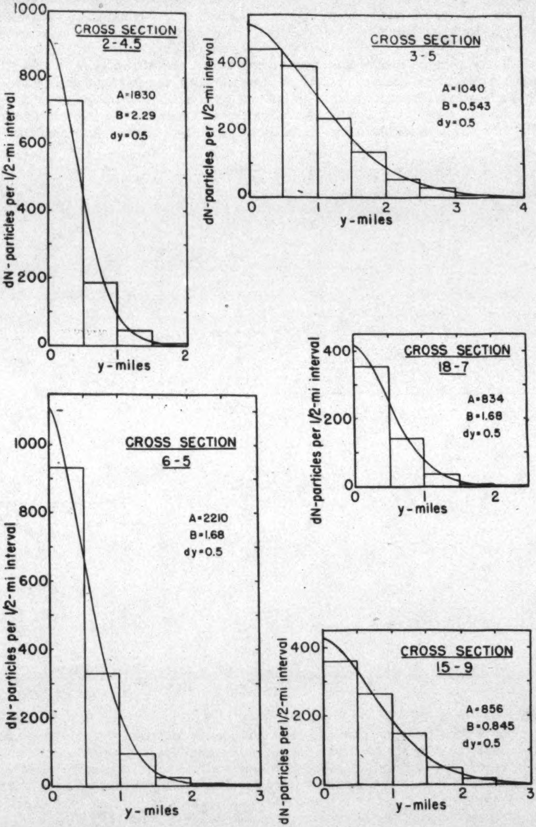

Fig. 7--Histograms of horizontal particle distributions; centers of gravity of individual passes aligned; curves of the form $dN = A\exp(-By^{1.7})\,dy$

Whatever the cause of the differences in breadth between the particle distributions in individual passes and the distributions in Figure 6, the distributions found on the average in individual passes are of some interest. These were determined by proceeding as for Figure 6, except that the count for each pass was first translated laterally until its individual center of gravity fell on the axis $y = 0$. The results are shown in the histograms of Figure 7.

It appeared that equations of the form of (4) were as appropriate for the distributions of Figure 7 as for the time-mean distributions of Figure 6 and that the spread of values of n was much smaller than the spread in Figure 6. In fact, a compromise value of $n = 1.7$ in all five cases gave about as good representations as the precision of the data justified. The curves in Figure 7 were calculated with $n = 1.7$, the parameters A and B being adjusted by trial and error. No great precision is attainable in the determination of a best value for n since the trend of the curves over considerable portions is not very sensitive to changes in n, and changes in n can be compensated partially by adjustment of A and B. Variations in n as great as ±0.15 ordinarily do, however, produce significant changes in the goodness of fit to the experimental data.

Cross section 2-4.5 has been included in Figure 7 since, for the purposes of this study, it is not necessary to know the original alignment of the counts. For this cross section we find a large value of B (2.29); this result suggests that the 2-4.5 cross section, as well as the 18-7 cross section, was not subject to much crosswise wind shear. Inspection of the pilot-balloon data verifies this.

If the ordinates in Figure 7 are divided by the number of passes made in each case, a curve can be obtained applying on the average to individual passes through the plume. Then, taking into account the airplane speed and the sampling rate, the constants for a concentration equation of the form of (3) can be obtained. We shall write this equation

$$C = C_m \exp(-By^n) \quad \ldots\ldots\ldots\ldots \quad (5)$$

It is understood that (5) applies to the aspect of the plume seen on the average in individual passes; the omission of the overlines serves to distinguish it from (3). The new aspect of the plume can be regarded as an approach to Sutton's 'instantaneous aspect.'

Table 3 shows the parameters in (5) for each of the five cross sections, together with results of particle-flux calculations and the plume-width ratios (ratios of plume width to distance from the source). The plume width is taken as the lateral distance between points where the concentration is one-tenth of the maximum, as determined from the curves in Figure 7. The approximate particle flux is calculated by using the average particle concentration, the plume cross section, and the approximate wind speed.

Table 3--Parameters for Equation (5) and particle-flux calculations (1952 tests)

Cross section	Number of passes	C_m	B	Plume area	Wind speed	Particle flux	Plume width ratio
		particles/m^3		m^2	m/sec	particles/sec	
2-4.5	7	7000	2.29	4.6×10^6	4.9	4.3×10^{10}	0.89
3-5	11	2500	0.543	18.4×10^6	5.4	9.1×10^{10}	1.86
6-5	10	5900	1.68	11.6×10^6	5.4	9.6×10^{10}	0.96
18-7	9	2500	1.68	9.3×10^6	4.0	3.0×10^{10}	0.70
15-9	5	4600	0.845	9.6×10^6	3.1	4.5×10^{10}	0.80

Note: Parameter n is given the value 1.7.

The particle fluxes in Table 3 are to be compared with the output of the source, which was about 8×10^{10} particles/sec. For cross sections 3-5 and 6-5, the agreement is perhaps as good as should be expected in this kind of experiment. In the other three cases the discrepancies probably reflect errors in estimating the appropriate wind speed and plume height. The plume height ordinarily was taken to be midway between two levels where particles were seen on one level but not on the one 500 ft higher. Visual observations on smoke plumes indicate that the top of a plume may be very 'bumpy,' and considerable error may result from this procedure.

It is noteworthy that the width ratios fall within a fairly narrow range except for cross section 3-5, where the width ratio is almost double that of the comparable cross section 6-5. In the case of 6-5, the fact that large changes in B and n occur between Figures 6 and 7 suggests that the small B and large n in Figure 6 probably were more the result of meandering than of crosswise shear. It then would be supposed that for 3-5 the turbulence and possibly the crosswise shear were considerably more severe than for 6-5. It is unfortunate that gustiness measurements were not made for 3-5.

Analysis of 1951 data

After the above work was done with the 1952 data, it became of interest to see if the 1951 data could be fitted into the same pattern. Because of the smaller output of the source (3×10^{10} particles/sec) and the slower sampling rate (35 ℓ/min), the numbers of particles collected per mile of flight were much smaller than those collected in 1952. Nevertheless, four cross sections were found to have data sufficiently complete for the purpose.

The timing uncertainties in the 1951 tests were somewhat greater than in the 1952 work, so the studies included only the aspect seen on the average in individual passes. The analysis began with determination of the centers of gravity of the counts in individual passes, after which the counts were translated so that the centers of gravity were in vertical alignment. Summations were made in the same manner as for Figure 7, and curves of the form of (4) were fitted to the histograms. Intervals of one-half mile were used for cross section M-5; but, because of the sparseness of the counts, one-mile intervals were used for the other three. (The numeral in the cross-section designation gives, as before, the distance in miles from the source to the cross section.) In spite of the small numbers in the counts, the fits were comparable to those in Figure 7.

Table 4--Parameters for Equation (5) and other data (1951 tests)

Cross section	Date flown	Number of passes	C_m[a]	B	Wind speed	Plume width ratio
			particles/m^3		m/sec	
M-5	May 18	6	4700	0.80	6.3	0.72
Q-12	May 24	6	350	0.10	8.9	1.05
N-14	May 21	4	910	0.47	13.4	0.36
I-22	May 15	5	720	0.22	11.2	0.36

Note: Parameter n is given the value 1.7.

[a] Adjusted to correspond to a source output of 8×10^{10} particles/sec.

The concentration distributions were calculated in the form of (5), the resulting parameters being shown in Table 4. The values of C_m shown were obtained by multiplying the actual values by 8/3, thus adjusting the values of C_m to correspond to a source output of 8×10^{10} particles/sec. The values of C_m in Table 4 then can be compared directly with the values of C_m in Table 3. Particle fluxes are not shown for the 1951 cross sections because the explorations in most cases did not establish the plume heights.

Table 4 shows two width ratios, those for N-14 and I-22, that are far below the range found in the 1952 tests; the other two are within the 1952 range. Study of the pilot-balloon record indicates that crosswise shear for all the 1951 tests was comparable with, or smaller than, that for 2-4.5 and 18-7 in the 1952 tests. The general wind speed for N-14 and I-22 was considerably higher than for any of the other tests; this, of course, results in low values for C_m and may have some bearing on the width ratios. In the absence of any other explanation, the low values of B and C_m for Q-12 would seem to indicate rather severe turbulence.

Analysis of Australian data of 1953

In the Australian tests, the securing of data on ZnS particle distribution was more or less incidental to other work, so the explorations of plume cross sections were not quite so systematic as the 1952 explorations in New Mexico. The results are particularly interesting, however, because they were obtained under winter conditions.

Data from six plume cross sections were analyzed in the same manner as were the New Mexico data of 1951, and the horizontal distributions found on the average in individual passes were determined. The results, together with other data on the plumes, are shown in Table 5. Even with the alignment of the centers of gravity of the collections made in single passes, it was not always possible to fit the data with the value 1.7 assigned to the parameter n, so the table shows all three parameters, C_m, B, and n, in (5).

Table 5--Parameters for Equation (5) and other data (1953 Australian tests)

Cross section	Date flown	Number of passes	C_m[a]	B	n	Plume height	Wind speed	Plume width ratio
			particles/m^3			ft	m/sec	
A3-3	July 24	4	25,400	0.50	2.0	1600	1.9	1.33
A5-4	July 29	8	3,800	0.55	2.5	5000	8.2	0.90
A1-5	July 9	11	32,600	2.50	1.7	2200	3.1	0.38
A10-6	Sep. 1	6[b]	7,800	2.14	1.7	....	6.7	0.35
A6-7	July 30	9	6,300	2.03	1.7	5000	4.8	0.31
A4-10	July 28	7	1,700	0.016	2.8	5500	4.1	1.18

[a] Adjusted to correspond to a source output of 8×10^{10} particles/sec.

[b] No passes above 1000 ft.

The very high values of C_m for A3-3 and A1-5 are results of confinement of the plume below a stable layer, together with low wind speeds. Crosswise shear was small for A1-5 but was considerable for A3-3, this difference being reflected in the plume-width ratios and in the values for B. For A5-4, on the other hand, the lapse rate was dry adiabatic to well above the top of the plume; and there was a brisk wind with little crosswise shear. This case seems to weaken the thesis that the combination of n = 1.7 with relatively large values of B is appropriate in the absence of strong crosswise shear. Inspection of the original data suggests, however, that in this case we merely have an unusually severe departure from the distribution that would have been observed with an entirely adequate sampling. It happened that in three of the eight passes fairly strong double peaks were encountered.

A10-6 and A6-7 were made under small-to-moderate crosswise shear. There appeared to be weak stability above 3000 ft for A6-7, but this evidently did not limit the height of the plume. For A4-10 there again was considerable shear. Lapse-rate measurements indicated a slight tendency toward stability above 2500 ft, though this was not evident in the plume height. The effect of shear is evident in the parameters and plume width.

Conclusions

The present experiments have shown that with as few as four to 11 sampling passes through an aerosol plume from a point source, it is possible to demonstrate considerable regularity in the horizontal distribution of particle concentration. It is of some interest that the horizontal distributions are fairly well represented by equations of the form of (4) and (5), derived from (1), at distances of three to 22 miles from the source, both for highly approximate time-mean distributions and for the distributions met on the average on single passes through a plume. As should be expected, crosswise wind shear has an important effect on the distributions, which is reflected in the parameters determined for (4) and (5).

The data did not permit verification of the presence of a vertical distribution of the form suggested by (1). Under the conditions of the 1951-1953 tests, there appeared to be a tendency toward a uniform vertical distribution over a considerable portion of the depth of a plume, presumably as a result of vigorous vertical mixing. The vertical mixing usually was sufficient to obscure distortion of the plume by crosswise wind shear.

It should be emphasized that the precision in determining parameters for (4) and (5) is not high enough, nor is the sampling adequate, to throw much light upon the theoretical aspects of the problem. As far as the sampling is concerned, it is difficult for one airplane to achieve adequate sampling even in plumes as narrow as five miles. Many of the explorations made in these studies required more than an hour to complete; and, in general, it cannot be expected that conditions affecting turbulent diffusion will remain constant for much longer than this.

The results of these studies have furnished additional evidence of the feasibility of diffusion and mixing studies on a scale of tens of miles, using a fluorescent aerosol as a tagging material. In view of the effect of such factors as crosswise wind shear and limiting stable layers, it seems difficult at the present to go much beyond an empirical approach. If knowledge of the phenomena is to be advanced much by this kind of investigation, the experiments should be more elaborate than they have been so far. A great deal of sampling will have to be done under varying conditions, and instrumentation will have to be provided to furnish a description as complete as is possible of the state of the entire volume of air involved.

Acknowledgment

For the 1951 and 1952 tests, the authors are greatly indebted to Robert Stubblefield of the Cutter-Carr Air Service, who piloted the twin-engine Beechcraft with precision on the courses prescribed. For the 1952 tests, they are indebted to T. A. Voorhees for assistance in navigation and in counting the ZnS particles in the collections, and to J. M. Lang for gathering and summarizing meteorological information.

For the 1953 tests in Australia, the authors are indebted to E. G. Bowen, head of the Radiophysics Sections of the CSIRO, who made the general arrangements; to E. J. Smith who supervised the special project; and to the Royal Australian Air Force which furnished the Dakota airplane and most of the personnel.

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TIDE-GAGE DISTURBANCES FROM THE GREAT ERUPTION OF KRAKATOA

Maurice Ewing and Frank Press

(Lamont Geological Observatory of Columbia University, Contribution No. 146)

Abstract--The aerial disturbance from Krakatoa was recorded at many stations on at least three passages around the Earth. A wave on the ocean was recorded at tide stations in almost all parts of the world. Only at nearby stations did the arrival times uniformly agree with that expected for gravity waves in the ocean; many distant arrivals were attributed to coincidental local earthquakes. It is shown that the tide-gage disturbances at distant stations correlate in time with the first aerial wave arriving at the station in the direction from ocean to continent, a result which would be expected from coupling between the barometric disturbance and the ocean surface wave. These observations have led to theoretical and experimental investigations of several types of air-coupled surface waves.

Introduction--Krakatoa, a small volcano in Sunda Strait, is famous for its eruption in 1883 which was accompanied by one of the greatest explosions ever recorded. A remarkable feature of the explosion was the barometric disturbance which traveled outward from the volcano and was recorded at many stations on at least three passages around the Earth. A disastrous tsunami was initiated, and oscillations were recorded by tide gages as far away as San Francisco, Colon, and several English Channel ports.

The conclusions on propagation of the tide-gage disturbances which had been reached by Wharton in the Royal Society Committee report may be summarized as follows: (1) To the north and east in the Java Sea the waves could be traced for 450 mi, at which point they were reduced to small amplitudes. (2) To the south and east the propagation was limited, not extending beyond the west coast of Australia. (3) To the west the waves traveled over great distances, reaching Cape Horn and possibly the English Channel, the Cape Horn paths being very improbable because the velocity required great water depth in unsurveyed Antarctic waters. (4) The disturbances in the Pacific and in the Caribbean had no connection with Krakatoa, but were the results of other seismic actions, and were apparently due to more than one center of movement.

Reference to the chart, Plate XXXV of Wharton's report [SYMONS, 1888] shows that the Indian Ocean stations (and possibly Port Moltke, South Georgia) are the only ones to which an ocean wave can travel without demanding improbable refraction or diffraction around barriers. For example, the paths to Hawaii, Kodiak, and San Francisco must be deflected almost 180° in passing around Australia. Likewise, the paths to Colon and to the English Channel ports must swing sharply to round the Cape of Good Hope, and even after that must cross severe barriers. The difficulty of transmitting energy over these paths, as well as the impossible velocities to which they led, justified Wharton's doubt that the observed energy was propagated as water waves along these paths.

In this paper it is suggested that energy in the wave recorded at large distances was transferred to the water from the barometric disturbance when this disturbance approached the station from the Ocean side. Until this mode of transmission of energy to these stations was suggested, there seemed no alternative but to follow Wharton's conclusion that unrelated seismic disturbances were responsible for the waves.

It is of interest to note that, although VERBEEK [1886] noticed the simultaneous arrival of the aerial wave and the tide-gage disturbance at Colon, he passed this off as a coincidence and ascribed the ocean wave to a near earthquake.

Presentation of data--The published tide-gage records for the Krakatoa disturbance were examined to see if any part of the indication could be correlated with the arrival time of the air wave. It was immediately noted that, for the stations beyond the Indian Ocean which Wharton could not correlate with the Krakatoa explosion on the assumption of propagation as a gravity sea wave, the arrival time of the major tide-gage disturbance could be correlated with the arrival of the first or second air wave.

Table 1--Air- and sea-wave arrival times (Local Civil Time)

Location	Air-wave arrival hours after 00h August 27, 1883		Air-wave arrival		Wharton's time of sea-wave travel in shallow water	Wharton's observed sea-wave arrival		Expected time of arrival for air-induced sea wave[c]		Our observed sea-wave arrival time		Expected minus observed air-sea wave	
	I[a]	II[b]	I[a]	II[b]		Commencement	First great wave	I[a]	II[b]	I[a]	II[b]	I[a]	II[b]
	h m	h m	d h m	d h m	min	d h m	d h m	d h m	d h m	d h m	d h m	h m	h m
Port Moltke (South Georgia)	15 15	28 00	27 12 48	28 01 33	7	27 14 00	28 01 45	27 12 55	28 01 40	27 14 00	28 01 30	-01 05	+00 10
Orange Bay (Cape Horn)	16 00	27 00	27 11 28	27 22 28	63	27 14 20	27 21 57	27 12 31	27 23 31	27 14 00	27 21 50	-01 29	+01 41
Colon	20 30	22 00	27 15 10	27 16 40	25	......	27 16 30	27 15 35	27 17 05	27 15 15	?	+00 20	.....
Socoa	14 00	27 45	27 13 53	28 03 38	30	......	28 04 50	27 14 23[d]	28 04 08	d	28 04 50	d	-00 42
Rochefort	13 45	27 45	27 13 41	28 03 41	197	28 07 40	28 09 20	27 20 58[d]	28 06 58	d	28 07 30	d	-00 32
Devonport	14 00	27 45	27 13 43	28 03 28	184	28 06 20	28 10 45	27 16 47[d]	28 06 32	d	28 06 40	d	-00 08
Cherbourg	14 00	27 45	27 13 54	28 03 39	286	28 09 20	28 09 20	27 18 40[d]	28 08 25	d	28 09 20	d	-00 55
Portland	14 00	27 45	27 13 50	28 03 35	274	......	28 10 15	27 18 24[d]	28 08 09	d	28 07 20?	d	+00 49?
Havre	14 00	27 45	27 14 00	28 03 45	410	28 11 33	28 11 33	27 20 50[d]	28 10 35	d	28 11 33	d	-00 58
Williamstown (Australia)	08 30	34 00	27 18 09	28 19 39	138	......	28 04 40	27 20 27[d]	28 21 57	28 01 00	28 20 00?	d	+01 57?
Honolulu	14 00	28 45	27 03 29	27 18 14	11	26 14 00	27 03 20	27 03 40	27 18 25	27 03 20	......	+00 20	.....
St. Paul's (Kodiak)	13 30	30 00	27 03 22	27 19 52	88	27 01 30	27 16 45	27 04 50[d]	27 21 20	......	27 16 45	d	+04 35
Saucelito (San Francisco)	16 00	27 00	27 07 50	27 18 50	43	27 00 00	27 13 10	27 08 33	27 19 33[d]	27 09 40	d	-01 07	d

[a] Direct path.

[b] Path through Antipodes.

[c] Obtained by adding time of sea-wave travel in shallow water to air-wave arrival.

[d] Air-sea wave blocked by land

[e] Air-sea wave blocked by land; sea wave reflected from Antarctica (?).

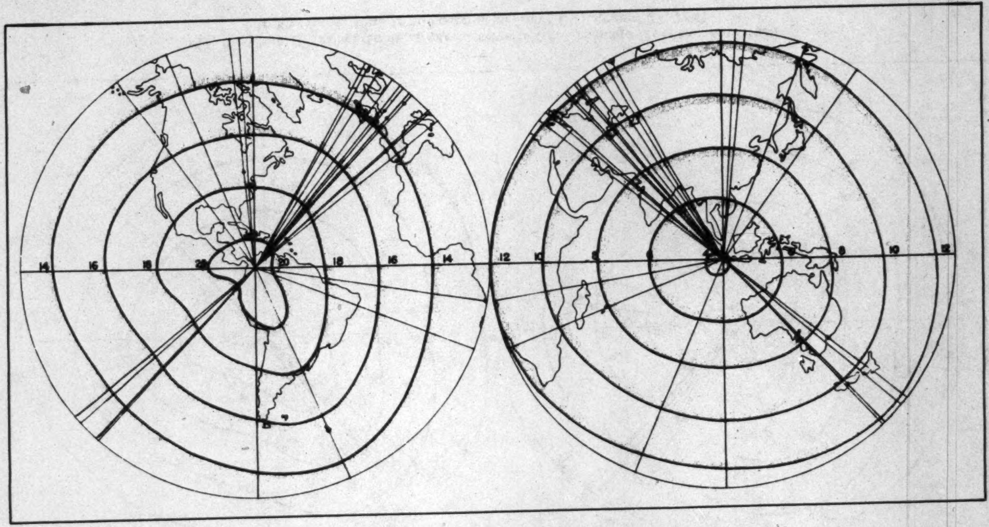
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Fig. 1--Wave I, travel times of aerial wave in first passage from Krakatoa to the Antipodes; time is in hours after 00h GCT, August 27, 1883

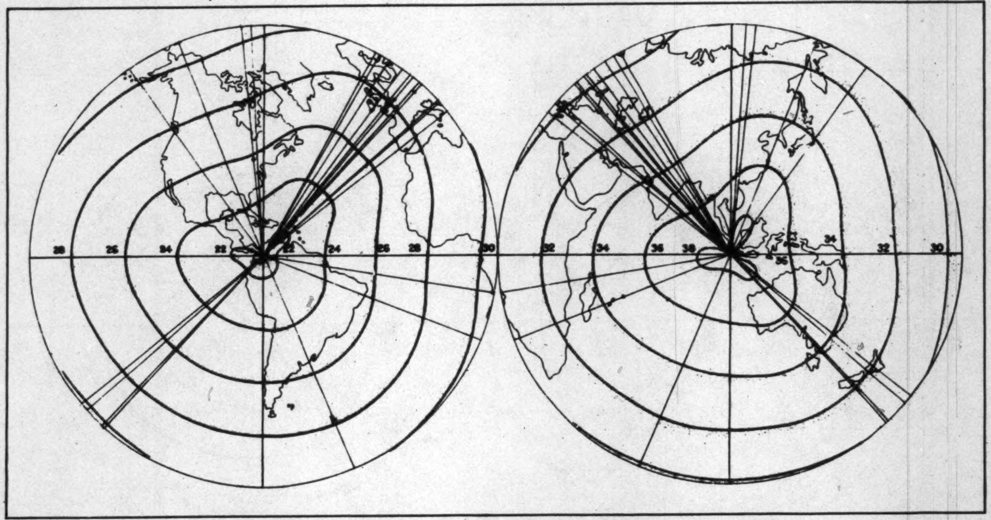
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Fig. 2--Wave-II, travel times of aerial wave in first passage from the Antipodes to Krakatoa; time is in hours after 00h GCT, August 27, 1883

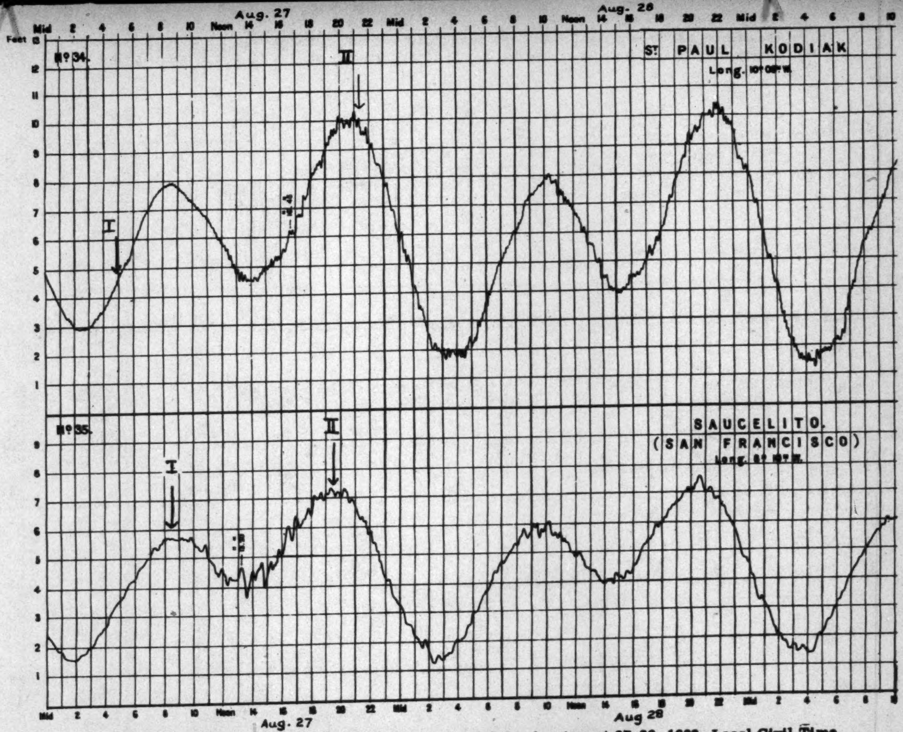

Fig. 3--Marigrams for South Georgia, Honolulu, and Colon for August 27-29, 1883, Local Civil Time [after SYMONS, 1888]; expected time for air-induced sea waves I and II is shown by arrows

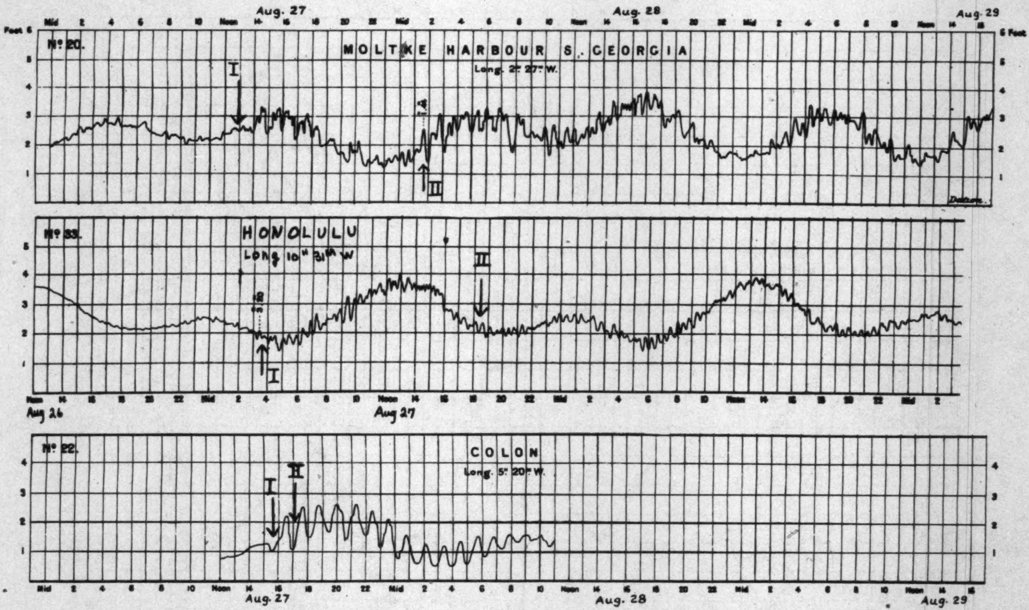

Fig. 4--Marigrams for Kodiak and San Francisco for August 27-29, 1883, Local Civil Time [after SYMONS, 1888]; expected time for air-induced sea waves I and II is shown by arrows

For those Indian Ocean stations for which the observations are good, reasonable paths are available for ordinary water waves, and the travel times are not in serious disagreement with those expected from this mode of propagation. These stations will not be discussed further except for the remark that in these cases the energy brought by the ordinary water wave greatly exceeds that induced from the air wave.

The paths and travel times of the first and second passages of the barometric disturbance are shown in Figures 1 and 2, taken from Strachey's article in the Report of the Royal Society [SYMONS, 1888]. The tide stations outside the Indian Ocean discussed by Wharton are listed in Table 1. Included in the table are the local times of arrival of the air wave as deduced from Figures 1 and 2, the expected time of arrival of the air-induced water wave computed by adding Wharton's allowance for propagation in shallow water near the station, and Wharton's and our arrival times for the gage disturbance as read from the published marigrams.

Wharton's readings from the marigrams differ from ours for the stations at Colon, Portland, Williamstown, Honolulu, St. Paul, and San Francisco. On the Colon marigram (Fig. 3), we picked the sharp commencement whereas Wharton read the peak of the first great wave an hour and a quarter later. We cannot agree to Wharton's reading for the commencement at San Francisco (Fig. 4) and have chosen instead the long waves beginning at 27-09-40. Similarly, at Honolulu and St. Paul (Fig. 3 and 4), we disregard the minor disturbance read as the commencement by Wharton (for Honolulu this occurs at a time prior to the major explosion at Krakatoa) and agree with this time for the first great wave. The disturbances on the Williamstown and Portland records are small, and any reading is open to some question.

Expected minus observed times for the air-induced sea waves are listed in Table 1. In nine cases the differences are less than one hour, and in five cases the differences range from one to two hours. In one case, St. Paul, the difference is four and a half hours. It is significant that the gage disturbances at the English Channel stations correlate with air wave II, which arrives from the ocean side via the Antipodes, rather than with the direct wave I which arrives from the land side. Excellent indications of waves I and II may be found on the Port Moltke marigram (Fig. 3). These correlations may well be expected if the gage disturbances were induced by the air wave. The discrepancy at St. Paul may be due to the fact that wave I is blocked by the Alaskan Peninsula and wave II is almost blocked by the North American mainland.

Discussion--The hypothesis of air coupling can well explain the origin of the tide-gage disturbances recorded at remote stations on August 27-29, 1883, and relates these disturbances to the Krakatoa explosion.

Experimental and theoretical investigations carried out subsequently to this study have indeed verified that coupling of surface waves to the atmosphere is an important factor in Rayleigh wave propagation from earthquakes or explosions [HASKELL, 1951; PRESS and EWING, 1951a; BENIOFF, EWING, and PRESS, 1951] and in flexural wave transmission in floating ice sheets [PRESS and EWING, 1951b; PRESS, CRARY, OLIVER, and KATZ, 1951]. In general, the greater the density contrast between the two media, the greater the need for equality of velocities in them, leading to a concept of resonant coupling at a period where the phase velocities in the two media (taken separately) are equal.

The absence of a known free wave in the ocean with phase velocity equal to the speed of the Krakatoa air wave (~1100 km/hr) suggests two possibilities: (1) significant coupling to the ocean can occur 'off resonance,' or (2) a free surface ocean wave with a speed close to 1100 km/hr exists. These possibilities are now being investigated.

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FLOW OVER REEFS AND STRUCTURES BY WAVE ACTION

Osvald Sibul

Abstract--The discharge of water caused by wave action on reefs and structures with impermeable, uniformly sloping sides and zero crest widths was measured for various elevations of crest with respect to the still-water level. The experiments were completed for side slopes of 1/2 and 1/3 and for smooth and rough surfaces of the barrier. The wave steepness H/L and the relative depth d/L were used as parameters, and dimensionless plots were made for the discharge QT/H^2 as a function of relative elevation h/H of the crest of the barrier.

Introduction--The crests of natural reefs generally are at or below the mean tide level. It has long been observed that waves breaking over a reef will 'pump' water over the reef. This water then usually flows along the lee side of the reef and returns to the open sea through a gap or inlet. In times of 'high' wave action the currents through such inlets may be relatively large and even make navigation of surface craft quite hazardous.

In the case of man-made structures such as levees and dikes, the crests are located well above the maximum expected high water. Extreme tides, wind tides, or flood conditions, however, may raise the water stage to such a level that wave action on the windward side might cause wave run-up to be excessive and pump an appreciable quantity of water over the structure, and thereby create a flood condition in the area protected by the structure. A disaster of this type occurred in Holland and Great Britain in February, 1953, where the loss in property and human lives was enormous. Not only must such structures be designed to withstand the static, dynamic, and erosive forces, but the crest elevations also must be sufficiently high to prevent overflow of water by wave action.

There appear to be few data available to permit a prediction of wave run-up on shore protection structures under a wide variety of conditions; the available information indicates, however, that wave run-up might amount to twice the wave height or sometimes even more [GRANTHEM, 1953]. Considering high-tide ranges for some areas and considerable wind tides [KEULEGAN, 1951; U. S. ENGINEERS, 1954], it is possible that very high structures may be necessary for some localities in order to prevent overtopping. Such high structures usually are very expensive, and a reduction of design height by only a foot might result in considerable savings in construction costs.

As in the case of wave run-up, there is little information available on the quantity of water that might be pumped over various types of structures by wave action. The first known experiments in this direction were completed by SAVILLE and CALDWELL [1953] for a vertical-faced sea wall. The results probably will not apply for other types of structures. To fill this gap in our knowledge, the series of tests described below was performed in the Wave Research Laboratory of the University of California. The tests were conducted on structures with a uniformly sloping, impermeable face, but with zero crest width. Two different side slopes were investigated (1/2 and 1/3) under a variety of wave conditions. The results are given as dimensionless plots of the variables involved.

Laboratory equipment and procedure--The experiments were conducted in a glass-walled wave channel one foot wide by three feet deep by 60 ft long. Waves were generated by a flapper-type generator mounted at one end of the channel. Both the amplitude and the period of the flapper movement were adjustable. The period could be varied between approximately 0.4 and two seconds, and the maximum wave height was about 0.5 ft. The water depth during all experiments was 1.69 ft.

The model was located approximately 45 ft from the wave generator and was built in the form of a sheet-iron box as shown in Figure 1. The front end of the model, representing the structure, consisted of a sloping board. The slope of the board could be varied by rotating it around point A (Fig. 1), and the crest elevation of the structure could be placed at various positions above or below the still-water level. Special care was taken to seal all the cracks between the structure and the channel walls, so that water circulation could not occur. The roughness of the structure was varied by using different plates fastened on the surface of the sloping board. The smooth surface

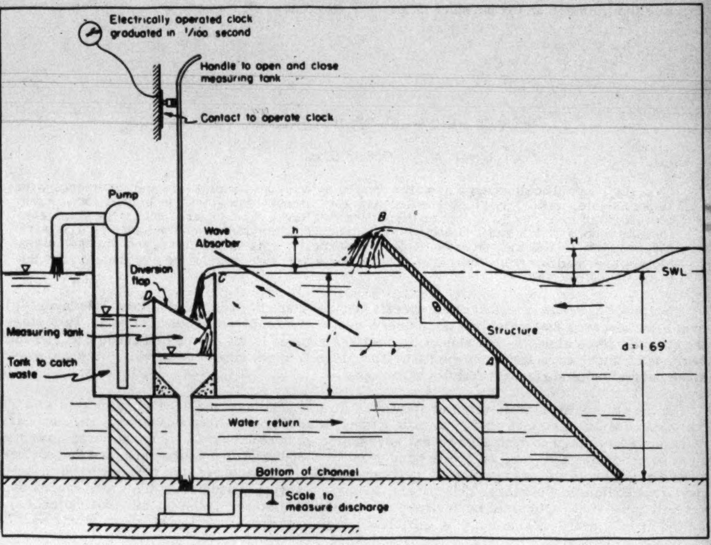
Electrically operated clock graduated in 1/100 second
Handle to open and close measuring tank
Contact to operate clock
Pump
Wave Absorber
h
B
H
Diversion flap
C
D
SWL
Measuring tank
Tank to catch waste
Structure
θ
A
l'
d = 1.69'
Water return
Bottom of channel
Scale to measure discharge

Fig. 1--Sketch of set-up

was represented by a smooth aluminum sheet, while for a rough surface transverse wood strips were fastened to the aluminum sheet (Fig. 2). The equivalent sand roughness was found to be 0.036 ft for the smooth surface and 0.13 ft for the rough surface [JOHNSON, 1944].

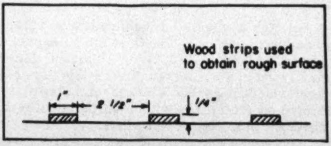
Wood strips used to obtain rough surface
1"
2 1/2"
1/4"

Fig. 2--Artificial roughness used in experiments

Water that was pumped over the structure by wave action was caught in a measuring tank, and the discharge was determined gravimetrically. The tank was arranged so that the water passing over the structure could be diverted either into the measuring tank or into a waste area. The arrangement was necessary to permit the measurement of discharge for any chosen wave group or for a fixed length of time. The handle of the diversion flap was arranged so that a contact to an electrically operated clock was closed the moment the flap was opened to the measuring tank and the contact cut again when the flap was closed. This arrangement permitted very accurate timing. The clock was graduated to give a least reading of 0.01 sec. The water in the waste tank was returned to the channel at the back side of the model by means of an auxiliary pump which operated continuously. This water could return again to the main channel and thereby maintain the depth of water therein a constant. A wave absorber was placed between the structure and the measuring tank so that the flow over edge C (Fig. 1) would be more regular and not affected by the turbulence of the breaking waves. The absorber also was particularly important for the case where the edge B of the structure was below the still-water level.

The wave heights and periods were measured about two to four wave lengths seaward of the structure. Wave heights were measured by a double wire resistance element and a Brush recorder.

__Procedure__--The structure was given a desired slope θ and the edge B set to a certain height h above (or below) still-water level. The value of h was taken as positive when the crest of the structure was above the still-water level, and as negative when below the still-water level. The average value for h was obtained by measuring the elevation with a point gage at three locations, at least, across the channel. In order to permit equilibrium conditions to exist after starting the wave generator, the water pumped over the structure by the first three or four waves was diverted to the waste area, and then the measurement of water pumped was made of the following three to ten waves according to the capacity of the measuring tank. Special care was taken to limit the measurement to the time before reflected waves from the structure could reach the wave generator and return to the structure. After the wave generator was stopped, the volume of the water collected in the measuring tank, the number of waves acting on the structure, and the duration of the measurement as obtained from the electrically operated clock were recorded. The measurements were repeated five times for each condition. In general, there was very little difference in measurements between runs made under the same conditions. The wave heights and periods were obtained from the tape of the Brush record, disregarding the first three or four waves and those which occurred after reflection effects became noticeable. By examining the wave records, it was relatively easy to recognize the point where the reflection from the structure started to change the wave characteristics. The wave heights and periods as used represent the wave condition in the given depth of water as though no structure was present. A set of experiments usually was started with the crest of the structure approximately one wave height below the still-water level, and the crest was raised for the following runs in increments of approximately 0.05 ft until an elevation h above still-water level was reached where no appreciable overtopping of the structure occurred. Usually 40 to 50 single runs were completed for each set of experiments. Before starting each succeeding run, the water surface was permitted to quiet completely.

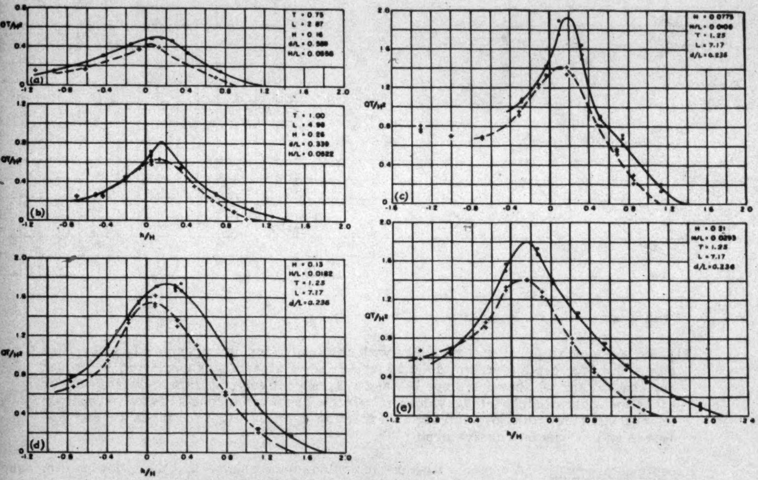

Fig. 3--Wave overtopping on marine structure as a function of relative height of structure; side slope, θ = 1/2; depth of water, d = 1.69 ft; —•— smooth surface; —+— rough surface: (a) and (b) show for slope 1/2 and 1/3, respectively, the rate of overtopping as a function of crest height for two values of relative depth and a constant wave steepness; (c) to (e) show the rate of overtopping as a function of crest height for three wave steepnesses and a constant relative depth

The general test procedure was to select a given wave condition (H and T held constant) and then measure the discharge of water pumped over the structure for various elevations h of the crest. Tests were conducted under the following wave conditions:

(1) For a constant wave steepness H/L of about 0.055, tests were made with d/L values of 0.339 and 0.589. The discharge passing over the structure was determined for several relative crest elevations h/H.

(2) For a constant relative depth d/L of 0.236, tests were made with wave steepness H/L of 0.0108, 0.0182, and 0.0293. Here again the discharge passing over the structure was determined for several relative crest elevations h/H.

For each of the above wave conditions, tests were made with face slopes of 1/2 and 1/3 and with both smooth and rough surfaces. The crest width in all tests was zero. A summary of test conditions is given in Table 1. The experimental data from the various runs are plotted in Figures 3 and 4.

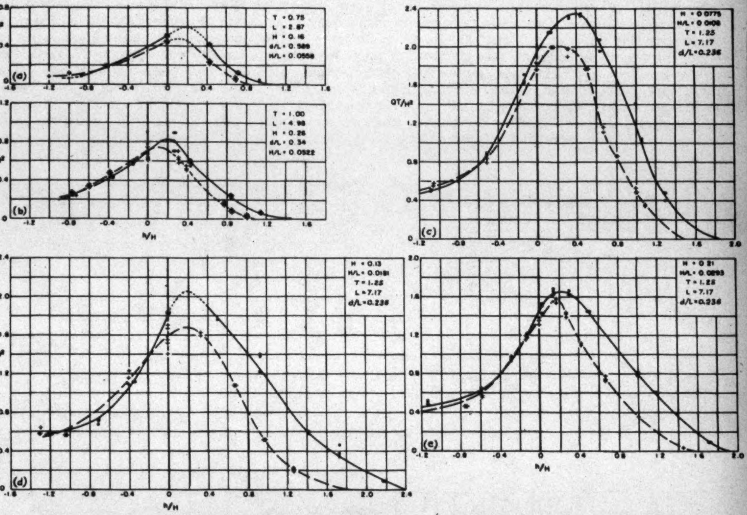

Fig. 4--Wave overtopping on a structure with uniformly sloping impermeable sides; side slope, θ = 1/3; depth of water, d = 1.69 ft; ——·—— smooth surface; ——+—— rough surface: (a) and (b) show for slope 1/2 and 1/3, respectively, the rate of overtopping as a function of crest height for two values of relative depth and a constant wave steepness; (c) to (e) show the rate of overtopping as a function of crest height for three wave steepnesses and a constant relative depth

Experimental results--A consideration of the various terms shows that the following dimensionless groupings can be used to represent the relationship between the water passing over an impermeable structure and the other variables

$$QT/H^2 = f\,(h/H;\ d/L;\ H/L;\ B/H;\ k/H;\ \theta)$$

where

Q = water passing over the structure by wave action, cfs/ft of structure (ft^2/sec)
T = wave period, sec
L = wave length, ft

Table 1--Summary of test conditions

Run number	Slope of structure	Surface of structure	Depth of water d	Wave period T	Wave length L	Height H	H/L	d/L	Maximum Q^a	Maximum over-topping per crest of wave per foot of structure $Q_w{}^a$	Maximum $QT/H^{2\,a}$	Maximum uprush h/H	k/H
			ft	sec	ft	ft			cfs/ft	cfs/ft			
35-84	1/3	Smooth	1.69	0.75	2.87	0.16	0.0558	0.589	0.0200	0.0153	0.60	1.05	0.22
35-84	1/3	Rough	1.69	0.75	2.87	0.16	0.0558	0.589	0.0160	0.0120	0.47	0.85	0.81
85-131	1/3	Rough	1.69	1.00	4.98	0.26	0.0522	0.340	0.0500	0.0500	0.74	1.10	0.50
132-173	1/3	Smooth	1.69	1.00	4.98	0.26	0.0522	0.340	0.0570	0.0570	0.84	1.60	0.14
174-213	1/3	Smooth	1.69	1.25	7.17	0.130	0.0181	0.236	0.0276	0.0346	2.05	2.40	0.28
214-242	1/3	Rough	1.69	1.25	7.17	0.130	0.0181	0.236	0.0227	0.0284	1.68	1.90	1.0
243-281	1/3	Rough	1.69	1.25	7.17	0.21	0.0293	0.236	0.0550	0.0686	1.56	1.55	0.62
282-321	1/3	Smooth	1.69	1.25	7.17	0.21	0.0293	0.236	0.0585	0.0732	1.66	1.90	0.17
322-349	1/3	Smooth	1.69	1.25	7.17	0.0775	0.0108	0.236	0.0113	0.0131	2.35	1.85	0.46
350-377	1/3	Rough	1.69	1.25	7.17	0.0775	0.0108	0.236	0.0096	0.0120	2.00	1.50	0.17
378-399	1/2	Smooth	1.69	1.25	7.17	0.0775	0.0108	0.236	0.0092	0.0115	1.92	1.40	0.46
400-427	1/2	Rough	1.69	1.25	7.17	0.0775	0.0108	0.236	0.0068	0.0085	1.42	1.10	0.17
428-452	1/2	Rough	1.69	1.25	7.17	0.130	0.0182	0.236	0.0208	0.0260	1.54	1.50	1.00
453-474	1/2	Smooth	1.69	1.25	7.17	0.130	0.0182	0.236	0.0235	0.0294	1.74	1.80	0.28
475-500	1/2	Smooth	1.69	1.25	7.17	0.210	0.0293	0.236	0.0635	0.0795	1.80	2.14	0.17
501-520	1/2	Rough	1.69	1.25	7.17	0.210	0.0293	0.236	0.0492	0.0616	1.40	1.50	0.62
521-540	1/2	Rough	1.69	1.00	4.98	0.260	0.0522	0.339	0.0427	0.0427	0.63	1.14	0.50
541-556	1/2	Smooth	1.69	1.00	4.98	0.260	0.0522	0.339	0.0542	0.0542	0.80	1.45	0.14
557-573	1/2	Smooth	1.69	0.75	2.87	0.16	0.0558	0.589	0.0165	0.0128	0.50	1.18	0.22
574-584	1/2	Rough	1.69	0.75	2.87	0.16	0.0558	0.589	0.0142	0.0110	0.43	0.92	0.81

[a] The values obtained from Figures 3 and 4 as maximums from experimental curves.

H = wave height, ft
h = elevation of the structure above (or below) still-water level, ft
B = crest width, ft
k = equivalent sand roughness, ft
θ = slope of the structure

To demonstrate the relative effect of the variables, the test data are summarized in Figures 3 and 4. The crest width B in all tests was zero.

The effect of the relative crest elevation of the structure above or below the still-water level is demonstrated in Figures 3 and 4. Smooth curves have been drawn for all the various test conditions. In general, the shape of all the curves is very similar. The maximum overtopping seems to occur when the crest of the structure is slightly above the still-water level with an average value of h/H approximately 0.2. From this point on, the amount of overtopping water decreases as the crest of the structure is placed further below the still-water level. These results apply naturally only for the conditions where the still-water level is at the same elevation on both sides of the structures, which is the case for most harbor protection structures, reefs, and so forth. The condition where there is no water on the lee side of the structure would be the case of flow over a weir combined with surface wave action. This condition has been treated previously by GIBSON [1930].

As can be seen in Figures 3 and 4, the roughness of the face of a structure has a considerable effect on the amount of overtopping water. At the maximum rate of overtopping, the rough surface results in an amount approximately 20 pct less than the smooth surface (see Table 1 for values of k/H for the smooth and rough surfaces). For higher values of h/H this percentage is even higher. In general, the empirical curves indicate that the rate of overtopping on a structure with relatively rough sides may be 20 pct lower than on one with smooth sides. In the case where the edge of the structure is below the still-water elevation, the roughness does not influence the results appreciably. It seems even that in this region the rough surface results in higher overtopping for some cases. This seems to be logical, for a rough surface prevents the backflow of water more than a smooth surface.

Relative depth of water--d/L is also a factor that would influence the rate of flow over a reef or structure by wave action. The steepness of the waves approaching shallow water depends upon the relative depth of the water, and so does the critical steepness which is given by the formula

$$(H/L)_{\text{critical}} = 0.140 \tanh 2\pi d/L$$

A wave near the critical steepness for breaking can be easily 'tripped' and made to break by any outside disturbance. The location of the breaking point was found to be an important factor in the overflow by wave overtopping. When the wave broke just over the edge of the structure, the discharge caused by wave overtopping was relatively high. On the other hand, when breaking occurred before the wave reached the structure, considerable energy was lost, and the discharge by overtopping was relatively small.

Wave steepness--To compare the results obtained under various wave steepnesses, but with a constant d/L, the curves from Figures 3ce and 4ce were replotted in Figure 5. A comparison of the various curves shows that the maximum rate of overtopping generally was greatest for waves of small steepness. This is more evident in Figure 6, where the maximum values of QT/H^2 as obtained from the curves in Figure 5 are plotted as a function of wave steepness H/L. These curves indicate an increasing value for the maximum value of QT/H^2 as the wave steepness decreases. There appears to be a certain wave steepness which results in a maximum value of $(QT/H^2)_{max}$, however, considerably more data are necessary to draw more definite conclusions. Figure 6 indicates also a higher discharge of water for a structure with a side slope of 1/3 than for one with a slope of 1/2.

Wave run-up--To supplement the previous work on wave run-up by GRANTHEM [1953], data have been obtained from Figures 3 and 4. Wave run-up in this instance was equal to the elevation of the crest of the structure when the latter was just high enough to prevent overtopping. Thus, for the data shown in Figures 3 and 4 the wave run-up was computed from the relative crest elevation h/H at the point where the curve showed a zero discharge by overtopping. The computed values are plotted in Figure 7 as a function of wave steepness H/L for slopes 1/2 and 1/3 and for smooth and rough surfaces of the structure. Figure 7 indicates that there is a critical wave steepness which results in the highest run-up of the waves. The wave steepness determines the breaking

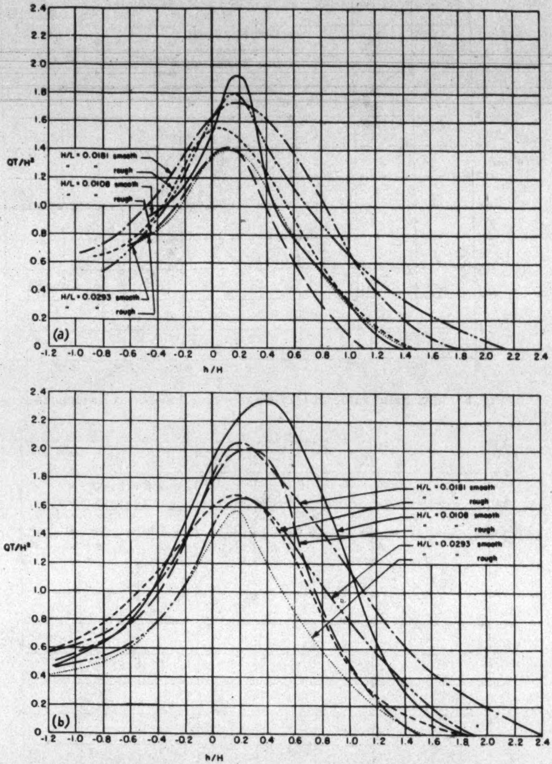

Fig. 5--Wave overtopping as a function of height of structure above still water for constant d/L ratio and variable wave steepness; d = 1.69 ft; T = 1.25 sec; L = 7.17 ft; d/L = 0.236; (a) θ = 1.2; (b) θ = 1.3

point, and when breaking occurs just at the edge of the structure the run-up is a maximum. When the breaking point moves seaward, the run-up decreases. When the waves do not break on the structure, the run-up decreases again with a decreasing wave steepness, and it is expected that it would reach the half wave height for very long waves (such as the tide). This is confirmed also by the fact that the curves in Figure 7 indicate a trend toward the value h/H = 0.5 for zero steepness. Figure 7 indicates also that there is a different critical steepness for different structures. For the slope 1/2, this critical H/L value is higher than for a 1/3 slope for the given wave condition.

As shown in Figure 7, the roughness of the structure also has an important bearing on the wave run-up. Thus run-up is about 30 pct higher for a smooth surface than for a rough surface.

Conclusions--Within the limits of the experiments on uniformly sloping, impermeable structures, it is concluded that:

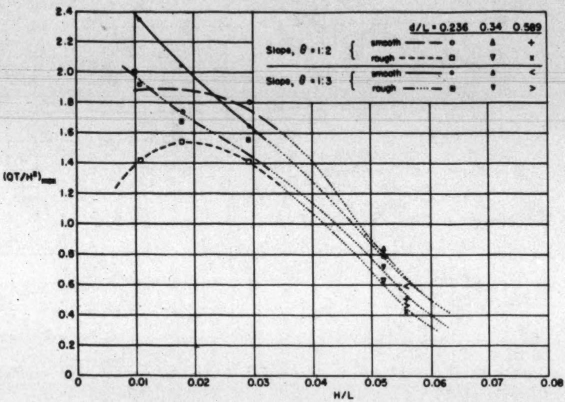

Fig. 6--Maximum value of QT/H^2 as a function of wave steepness

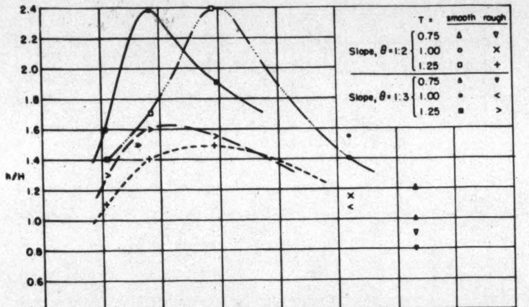

Fig. 7--Wave rush-up h/H on sloping structures
as a function of wave steepness

(1) For a given relative height of a structure and a given relative depth, the overtopping of water caused by wave action is largest for the structure with a smooth face.

(2) The maximum rate of overtopping occurs when the structure is approximately 1/5 wave height above the still-water level, provided that the still-water level is at the same elevation on both sides of the structure. For a given relative depth and surface roughness, the maximum rate of overtopping decreases as the wave steepness increases.

__Acknowledgments__--This study was part of an extensive investigation on waves and related phenomena sponsored by the Office of Naval Research. The author wishes to express his appreciation of the suggestions, supervision, and assistance of J. W. Johnson in carrying out the experiments and presenting the results.

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DISCUSSION

S. W. Yuan (University of California, Berkeley, Calif.)--As stated by the author, the data given pertain to reefs or structures with zero crest width. To give information on the effect of crest

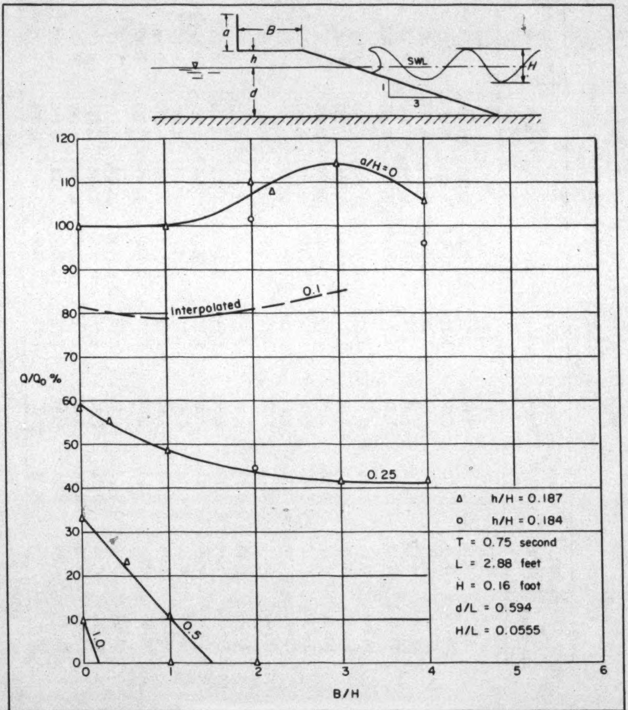

Fig. 8--Effect of crest width and parapet walls on wave overtopping

Table 2--Summary of test data

Run number	Wave height H	Wave period T	Wave length L	Depth of water d	H/L	d/L	h/H	Width of crest B	Height of vertical a	B/H	a/H	QT/H^2	Q/Q$_o$
	ft	sec	ft	ft				ft	ft				pct
1-6	0.16	0.75	2.88	1.71	0.0555	0.594	0.184	0	0	0	0	0.646	100
7-10	0.16	0.75	2.88	1.71	0.0555	0.594	0.184	0.32	0	2.0	0	0.657	101.7
11	0.16	0.75	2.88	1.71	0.0555	0.594	0.184	0.32	0.16	2.0	1.0	0	0
12-16	0.16	0.75	2.88	1.71	0.0555	0.594	0.184	0.32	0.04	2.0	0.25	0.288	44.6
17-20	0.16	0.75	2.88	1.71	0.0555	0.594	0.187	0.052	0.04	0.325	0.25	0.337	55.3
21-24	0.16	0.75	2.88	1.71	0.0555	0.594	0.184	0.64	0	4.0	0	0.621	96.0
25-29	0.16	0.75	2.88	1.71	0.0555	0.594	0.187	0.08	0.08	0.5	0.5	0.140	23.0
30-34	0.16	0.75	2.88	1.71	0.0555	0.594	0.187	0	0.08	0	0.5	0.202	33.2
35-38	0.16	0.75	2.88	1.71	0.0555	0.594	0.187	0	0.04	0	0.25	0.357	58.6
39-42	0.16	0.75	2.88	1.71	0.0555	0.594	0.187	0.16	0	1.0	0	0.606	99.6
43-46	0.16	0.75	2.88	1.71	0.0555	0.594	0.187	0.16	0.08	1.0	0.5	0.065	10.7
47-50	0.16	0.75	2.88	1.71	0.0555	0.594	0.187	0	0.16	0	1.0	0.0602	9.8
51	0.16	0.75	2.88	1.71	0.0555	0.594	0.187	0.16	0.16	1.0	1.0	0	0
52	0.16	0.75	2.88	1.71	0.0555	0.594	0.187	0.32	0.08	2.0	0.5	0	0
53-54	0.16	0.75	2.88	1.71	0.0555	0.594	0.187	0.16	0.04	1.0	0.25	0.295	48.5
55-59	0.16	0.75	2.88	1.71	0.0555	0.594	0.187	0.32	0	2.0	0	0.670	110
60-63	0.16	0.75	2.88	1.71	0.0555	0.594	0.187	0.36	0	2.25	0	0.658	108
64-67	0.16	0.75	2.88	1.71	0.0555	0.594	0.187	0.48	0	3.0	0	0.695	114
68-70	0.16	0.75	2.88	1.71	0.0555	0.594	0.187	0.48	0.04	3.0	0.25	0.252	41.4
71-74	0.16	0.75	2.88	1.71	0.0555	0.594	0.187	0.64	0	4.0	0	0.643	105.6
75-77	0.16	0.75	2.88	1.71	0.0555	0.594	0.187	0.64	0.04	4.0	0.25	0.253	41.5
78	0.16	0.75	2.88	1.71	0.0555	0.594	0.187	0	0	0	0	0.609	100

width, as well as parapet walls of various heights on the crest, the data shown in Table 2 and Figure 8 are presented. These tests were made with the same equipment used by Sibul. Tests were made with a relatively steep wave acting on a 1/3 slope, with the crest located at the most critical height for maximum rate of overtopping, that is, h/H values were 0.187 and 0.184. Crest widths B from zero to four wave heights H were tested with parapet walls of height a from zero to one wave height, located on the land edge of the crest. The upper curve of Figure 8 shows that with no parapet wall the flow over a levee actually will be greater with a crest up to about three wave heights in width over that occurring with zero crest width. As is evident from the other curves in the figure, appreciable reduction in overflow is achieved when walls only a fraction of a wave height high are installed. The installation of the parapet wall on the seaward edge of the crest gives a greater discharge for the same wall height than that shown in the figure. The effect of the wall on the seaward edge is to cause the water to be thrown approximately vertically when the wave strikes the wall, and the water then falls on the crest rather than returning seaward. The effect of the wall on the leeward edge of the crest, on the other hand, is to cause a water cushion to form on the crest from which water flows seaward and reduces the run-up of the oncoming waves.

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WIND-GENERATED OCEAN CURRENTS AT AMRUM BANK LIGHT SHIP

Hugo Mandelbaum

Abstract--A detailed study of wind-generated currents at a station with rotary tidal currents, based on the analysis of four-hourly observations during the years 1924-1933, was made at Amrum Bank Light vessel. The use of punch cards for the harmonic analysis of such bulky information is briefly explained. A 'residual current at calms' is defined and calculated to separate the wind-generated current from that caused by other forces. The wind-generated currents are calculated for winds of eight different directions. The influence of wind velocity and wind steadiness is investigated, and the functional relationship between wind and current is calculated. The water transport under various wind conditions is calculated, and finally charts are constructed which show the general current circulation in the German Bight of the North Sea at eight different wind situations.

Introduction--The purpose of this study is to investigate the influence of winds on periodic and non-periodic ocean currents. The observational records at Amrum Bank Light Ship were chosen for this investigation for several reasons. At Amrum Bank the tidal currents are of the rotary type, and one of the objectives is to find out whether the prevailing winds influence the form of the tide ellipse, not only the location of its center. A similar study on the influence of winds on the tide curve of an alternating tidal current has been carried out previously [MANDELBAUM, 1934]. Amrum Bank is the northernmost of the German light vessels in the German Bight. This makes it a suitable location for an investigation into the problem of the existence of separate eddy of the non-periodic currents in the German Bight. (See MANDELBAUM [1934] where more references are given concerning this particular problem.) Last, but not least, four-hourly observations of current and wind made on this vessel have been published by the DEUTSCHE SEEWARTE [1924 onwards]. Figure 1 shows the location of Amrum Bank Light Ship. The analysis is based on observations during a ten-year period, from 1924 to 1933. Since more than 22,000 observations were used, punch cards were used for the grouping of the observations according to tide phase, Moon age, and wind direction and velocity, and also for resolving the current vector into two mutually perpendicular components. Figure 2 shows a key-sort card especially designed for this purpose.

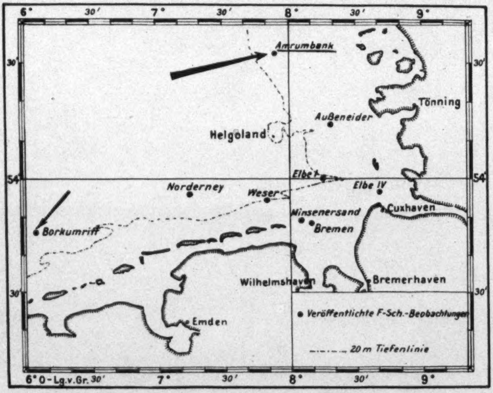
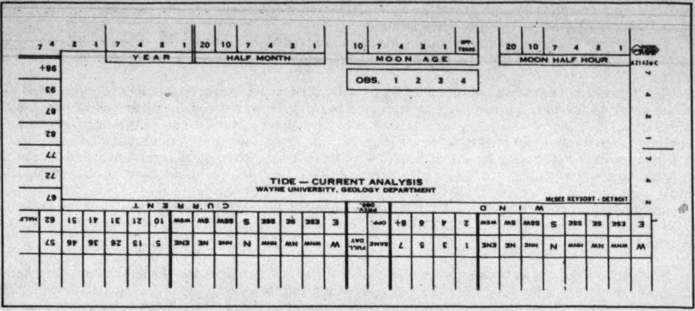


Fig. 1--German Light Ships in the North Sea (adapted from the publication of the Deutsche Seewarte)

IBM cards would have been more convenient for sorting and adding of punched-in components. However, the punching of the card requires trained clerical help which was not available for this project.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HALF MONTH
MOON AGE
MOON HALF HOUR
OBS. 1 2 3 4
TIDE — CURRENT ANALYSIS
WAYNE UNIVERSITY, GEOLOGY DEPARTMENT
CURRENT
WIND
McBEE KEYSORT - DETROIT

Fig. 2--Key-sort card used for this analysis

Punch card procedure for harmonic analysis--The cards were first machine-grooved in quantities for 24 different tide phases, called Moon half-hours, and distributed into a filer with 24 cubby holes (Fig. 3). The filer is so constructed that in each row the Moon half-hours of three consecutive observations are found. Into these three (or four) cards the Moon age of the observation was punched together, and the observational data were transferred onto the card by check marks.

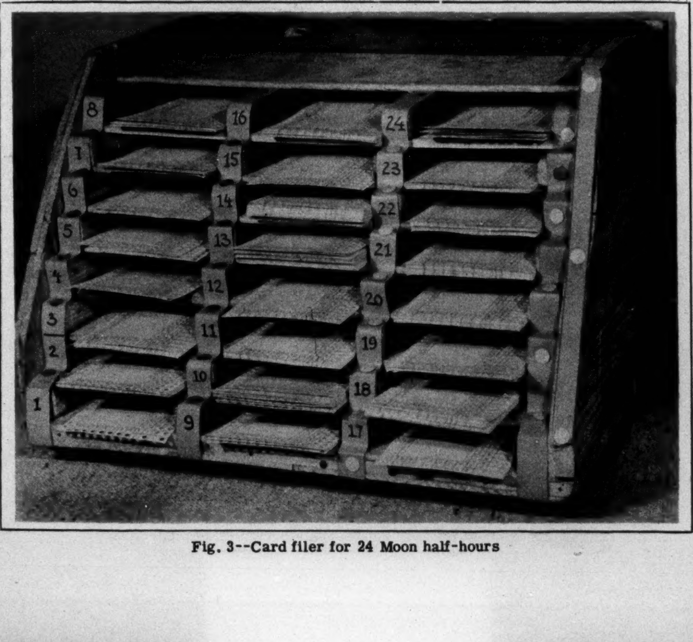
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Fig. 3--Card filer for 24 Moon half-hours

Finally, the numbers of the half-month and year were machine-punched into the card. The cards were then grouped according to current direction and subgrouped according to current velocity. Since the principal directions of the tide-current at Amrum Bank are NW-SE, the current vectors were resolved into NW and NE components. These components were group-punched into the cards. Then the cards were regrouped to Moon half-hours and were ready for the purpose of analysis. In the analysis the following groups were studied:

(1) Current observations at winds of eight wind directions (E and ESE, SE and SSE, etc.), subgrouped according to velocity: (a) forces 1 and 2 (Beaufort); (b) forces 3 and 4; and (c) force 5 and more.

(2) Current observations at winds of eight wind directions, subgrouped according to wind conditions prior to the time of observation: (a) wind blowing from a different direction at previous observation; (b) wind of the same direction at previous observation (winds of the same direction were considered those not deviating more than 22 1/2° from the wind at observation time); and (c) wind from the same quarter for at least 24 hr prior to the time of observation (winds from the same quarter were considered those not deviating more than 45° from the wind at observation time).

Further grouping, according to 12 different Moon ages of the semi-monthly period of the tides and for 12 lunar months of the year, can be carried out and is planned to compute seasonal changes of the residual current.

For each of the six groups enumerated, the NW and NE components of the current, punched into the cards, were added for all observations falling into the same Moon half-hour (that is, tide phase) and the sum divided by the number of observations. At very high wind velocity no current observations were made. At some hours only the current direction, but not its velocity, is given in the printed data. Cards containing such incomplete information were sorted out before the start of the computation. Likewise, all observations of the period July, 1930, to August 5, 1930, were discarded. All current directions for this period were given as NW or SE, which obviously was an unjustified simplification on the part of the observer, J. Cornils, since all other observers noted the current as rotary at all times.

Table 1--Tide current (total of all observations)

Moon half-hour	Number of observation	Current velocity M_n	
		NW component	NE component
		cm/sec	cm/sec
1	877	29.6	8.7
2	905	35.4	8.0
3	889	39.8	7.7
4	896	42.6	5.0
5	863	41.8	3.0
6	879	39.3	0.1
7	879	33.8	-1.6
8	872	28.2	-3.4
9	847	20.2	-4.5
10	869	10.0	-4.6
11	838	- 0.4	-3.9
12	846	-11.4	-2.9
13	861	-23.8	-1.7
14	861	-31.9	-0.7
15	895	-35.7	0.9
16	862	-35.6	1.5
17	900	-34.4	2.7
18	845	-29.5	4.8
19	870	-24.4	5.9
20	840	-16.9	6.3
21	832	- 9.1	6.6
22	838	2.3	7.3
23	825	12.1	9.2
24	879	22.7	9.0
Total and means	20,768	$R_w(M_n) = 4.36$	$R_e(M_n) = 2.64$

Table 1 lists as an example the components of the current so computed for all 20,768 observations combined. These computed means M_n are considered the values of the current components at the mid-mark of the time interval of one Moon half-hour. This assumption is, however, not quite valid when non-periodic criteria, such as the wind, determine the group selection. Only if the number of observations in each interval is large will the error be negligible. To increase the number of observations falling into one Moon half-hour, two wind directions were combined for subdividing the observations according to wind velocity and previous wind conditions. Nevertheless, for winds blowing out of the NE sector the number of observations in some intervals is small, especially for strong winds, sometimes as low as four. This makes it necessary to attach weights P_n to each of these means M_n before calculating the Fourier coefficients best approximating the given values. The large amount of numerical calculation involved makes the employment of large scale electronic computing methods advisable. (The data are in the process of being prepared for coding for the electronic digital computer Wainac at Wayne University.)

Average residual current--The mean of the 24 M_n is called here $R(M_n)$ and represents the component of the non-periodic residual current. From Table 1 we take the NW- and NE-components of the average residual current $R_w(M_n) = 4.36$ cm/sec and $R_e(M_n) = 2.64$ cm/sec. The resultant current $R(M_n)$ has a drift $v = 5.1$ cm/sec and sets in a direction $d = N\,13°\,W$ magnetic. The declination at Amrum Bank was 10° W in 1924 and 8° W in 1933. If we apply an average correction of 9° W, we get the value $d = N\,22°\,W$ true.

Residual current at calms--Table 2 contains the residual currents calculated on the basis of observations made under various wind conditions. R_n^0 indicates residual currents calculated for average winds. $R_n^1, R_n^2, \ldots, R_n^6$ are residual currents calculated for winds of different velocities and different degrees of steadiness respectively. The subscripts 1, 2, . . ., 8 indicate eight different wind directions starting with E-ESE and proceeding clockwise around the compass. The mean of eight R_n which we designate as $R(R_n)$ represents that current in which the direct influence of the wind is eliminated by assuming that the effects of opposite winds cancel each other. We call it, therefore, the 'residual currents at calms.' However, Table 2 shows that $R(R_n)$ varies significantly in velocity and in direction. The resultant velocity of the residual current at calms decreases with increasing wind velocity from $R(R_n^1) = 5.2$ cm/sec for weak winds to $R(R_n^3) = 4.2$ cm/sec for strong winds, and with increasing wind steadiness from $R(R_n^4) = 5.8$ cm/sec at changing winds to $R(R_n^6) = 4.2$ cm/sec at winds steady for 24 hours. Its direction has a larger W-component than the average residual current with an average deviation of about 9°. The greatest deviation (17°) is found at strong winds.

Table 2--NW- and NE-components of residual current, cm/sec

Wind direction	Component	At all winds		At winds of different forces						At winds of various degrees of steadiness					
				1 and 2		3 and 4		5 and more		Changing		Steady 4 hours		Steady 24 hours	
		R_n^0		R_n^1		R_n^2		R_n^3		R_n^4		R_n^5		R_n^6	
		NW	NE	NW	NE	NW	NE	NW	NE	NW	NE	NW	NE	NW	NE
E-ESE	R_1	9.4	-0.1	9.0	0.4	9.7	-0.2	10.5	-0.4	9.7	-0.4	9.1	0.6	9.5	-0.1
SE-SSE	R_2	8.8	4.3	8.1	4.3	9.5	4.6	10.0	4.0	7.5	4.8	9.9	4.4	8.1	3.5
S-SSW	R_3	7.8	7.8	7.2	6.2	7.5	8.3	7.6	10.8	7.1	5.9	7.2	8.5	8.4	8.5
SW-WSW	R_4	4.4	7.8	3.8	6.1	4.6	8.2	4.9	9.4	3.6	6.6	4.6	7.9	4.3	8.6
W-WNW	R_5	1.2	4.4	2.3	3.5	0.8	4.3	0.1	6.1	3.7	4.6	0.3	4.7	0.3	3.6
NW-NNW	R_6	-1.0	-1.5	0.5	-0.3	-1.5	-1.4	-2.5	-2.5	3.1	0.4	-1.3	-1.5	-2.6	-2.0
N-NNE	R_7	2.2	-4.0	3.0	-2.6	0.4	-4.5	-1.2	-7.2	2.5	-2.4	2.0	-4.4	-0.1	-5.0
NE-ENE	R_8	4.3	-3.6	4.8	-2.2	4.2	-4.1	2.5	-7.2	5.4	-2.5	4.4	-3.8	3.6	-4.4
Residual current at calms $R(R_n)$		4.64	1.89	4.84	1.92	4.40	1.88	3.98	1.20	5.32	2.12	4.54	2.07	3.94	1.59
Resultant drift		$R(R_n^0)=5.2$		$R(R_n^1)=5.2$		$R(R_n^2)=4.8$		$R(R_n^3)=4.2$		$R(R_n^4)=5.8$		$R(R_n^5)=5.0$		$R(R_n^6)=4.2$	
Direction (magnetic)		N 18° W		N 23° W		N 22° W		N 28° W		N 23° W		N 20° W		N 23° W	
Direction (true)		N 27° W		N 32° W		N 31° W		N 39° W		N 32° W		N 29° W		N 32° W	

The reason for the variation in velocity of the 'residual current at calms,' if calculated on the basis of observations made at winds of different degrees of steadiness, is obvious. At changing winds the effect of previously blowing winds is still felt in the water current, and the predominant winds, which in the German Bight blow from the SW sector, will influence the calculated $R(R_n)$. The currents caused by SW wind are N to NNE. The variation in velocity of the $R(R_n)$ with wind velocity has the same reason. Obviously the criteria for grouping observations according to wind steadiness and wind velocity are not independent of each other. Strong winds are also more steady winds. The equal velocity of $R(R_n^3) = R(R_n^6) = 4.2$ cm/sec shows that at very strong winds the influence of previous wind conditions on the 'residual current at calms' is as effectively eliminated as by grouping the observation for greatest steadiness of the wind.

Table 3--Wind frequency at Amrum Bank

Wind	Number of observation	A	B	C
E	1345	2434	398	0.16
ESE	1089			
SE	1320	2239	277	0.12
SSE	919			
S	1128	2467	386	0.15
SSW	1339			
SW	2030	3563	810	0.23
WSW	1527			
W	1807	3228	686	0.21
WNW	1421			
NW	1954	3046	705	0.23
NNW	1092			
N	918	1589	171	0.11
NNE	671			
NE	903	1774	209	0.12
ENE	871			

A--Frequency of all winds
B--Frequency of winds of force 5 or more
C--Ratio of strong wind to all winds

The deviation in the direction of the 'residual current at calms' $R(R_n)$ from the average residual current $R(M_n)$ can be understood in the following way.

(1) $R(R_n)$ is called 'residual current at calms' under the assumption that the currents caused by winds of opposite directions cancel each other in the calculation. This, however, is not quite correct. As it will be shown later, currents at offshore (easterly) winds are stronger than those at onshore winds because of the proximity of the coast. This could mean that the calculated deviation is not a real one. However, for strong winds, where the deviation is largest (17°), the asymmetry between currents caused by W-winds and those caused by E-winds is smallest; while the former lack space for development, the latter lack sufficient fetch for a strong current. The deviation of $R(R_n)$ from the direction of the average residual current $R(M_n)$ can therefore at least partly be considered real.

(2) $R(M_n)$ is strongly affected by the frequency of winds from various directions. The predominance of winds out of the SW quadrant will tend to increase the NE component of $R(M_n)$. Moreover, winds out of the SW and NE quadrant differ not only in frequency but also in the proportion of strong winds within the frequency; of SW winds 23 pct have wind force 5 or more, of NE winds only 12 pct (see Table 3). The influence of wind conditions prior to the time of observation also gives weight to the predominant wind direction from SW.

(3) The residual current at Amrum Bank caused by forces other than the wind has a velocity of about four cm/sec and sets in a direction N30° W true.

Pure wind-generated currents--The differences $D_n = R_n - R(R_n)$ shown in Tables 4 and 5 represent the currents generated by the wind only. These values were smoothed by least square methods to represent eight discrete values of the function $f(x) = A_0 + A_1 \cdot \cos x + B_1 \cdot \sin x$ where x indicates the direction of the wind going clockwise from zero to 360°. The constants A_1 and B_1 are so calculated that zero degree is at E, instead of halfway between E and ESE. The functions $f(x)$ are shown in Table 6. A_0 is identical with the residual current at calms $R(R_n)$. Tables 4 and 5 show, besides the differences $D_n = R_n - R(R_n)$, the smoothed values C_n for both current components, together with their resultant values.

Table 4--Residual currents (in cm/sec) generated by winds grouped according to wind force

Wind	Components (magnetic)				Resultant velocity		Difference from wind direction	Corrected resultant velocity
	NW		NE					
	D_n	C_n	D_n	C_n	v	d		
						°	°	
Forces 1 and 2								
E	4.2	2.7	-1.5	-1.9	3.2	280	10	4.4
ESE		3.6		-0.3	3.5	310	18	4.4
SE	3.3	3.9	2.4	1.4	4.1	333	19	4.5
SEE		3.6		2.8	4.6	353	15	4.6
S	2.4	2.8	4.3	3.8	4.8	9	9	4.8
SSW		1.6		4.3	4.6	26	3	4.6
SW	-1.0	0.1	4.2	4.0	4.1	44	-1	4.1
WSW		-1.4		3.2	3.5	68	1	3.5
W	-2.5	-2.7	1.6	1.9	3.2	100	10	3.2
WNW		-3.6		0.3	3.5	130	18	3.5
NW	-4.3	-3.9	-2.2	-1.4	4.1	153	19	4.1
NNW		-3.6		-2.8	4.6	173	15	4.6
N	-1.8	-2.8	-4.5	-3.8	4.8	189	9	4.8
NNE		-1.6		-4.3	4.6	206	3	4.6
NE	0.0	-0.1	-4.1	-4.0	4.1	229	-1	4.5
NNE		1.4		-3.2	3.5	248	1	4.4
Forces 3 and 4								
E	5.3	3.2	-2.1	-3.4	4.8	269	-1	5.7
ESE		4.7		-1.0	4.8	303	11	5.7
SE	5.1	5.5	2.7	1.6	5.8	332	17	6.0
SSE		5.4		4.0	6.8	351	13	6.8
S	3.1	4.5	6.4	5.8	7.3	7	7	7.3
SSW		2.9		6.6	7.3	21	-2	7.3
SW	0.2	0.9	6.3	6.5	6.6	37	-9	6.6
WSW		-1.2		5.4	5.6	59	-9	5.6
W	-3.6	-3.2	2.4	3.4	4.8	89	-1	4.8
WNW		-4.7		1.0	4.8	123	11	4.8
NW	-5.9	-5.5	-3.3	-1.6	5.8	152	17	5.8
NNW		-5.4		-4.0	6.8	171	13	6.8
N	-4.0	-4.5	-6.4	-5.8	7.3	187	7	7.3
NNE		-2.9		-6.6	7.3	201	-2	7.3
NE	-0.2	-0.9	-6.0	-6.5	6.6	217	-9	6.8
ENE		1.2		-5.4	5.6	239	-9	5.8
Forces 5 and more								
E	6.5	4.1	-1.6	-5.3	6.7	262	-7	6.8
ESE		5.6		-1.8	5.8	299	6	6.7
SE	6.0	6.3	2.8	2.0	6.6	333	18	6.7
SSE		6.0		5.5	8.2	358	20	8.2
S	3.6	4.8	9.6	8.1	9.4	13	13	9.4
SSW		2.9		9.5	10.0	28	6	10.0
SW	0.9	0.5	8.2	9.5	9.5	42	-1	9.5
WSW		-1.9		8.0	8.2	59	-9	8.2
W	-3.9	-4.1	4.9	5.3	6.7	82	-7	6.7
WNW		-5.6		1.8	5.8	119	6	5.8
NW	-6.5	-6.3	-3.7	-2.0	6.6	153	18	6.6
NNW		-6.0		-5.5	8.2	178	20	8.2
N	-5.2	-4.8	-9.4	-8.1	9.4	193	13	9.4
NNE		-2.9		-9.5	10.0	208	6	10.0
NE	-1.5	-0.5	-9.4	-9.5	9.5	222	-1	9.5
ENE		1.9		-8.0	8.2	239	-9	8.2

Table 5--Residual currents (in cm/sec) generated by winds grouped according to consistency of wind direction

Wind	Component				Resultant velocity	Wind	Component				Resultant velocity	A
	NW		NE				NW		NE			
	D_n	C_n	D_n	C_n			D_n	C_n	D_n	C_n		
All observations						**Changing winds**						
E	4.8	3.2	-2.0	-3.2	4.6	E	4.4	2.2	-2.5	-3.6	4.2	...
ESE		4.4		-0.9	4.5	ESE		2.9		-1.8	3.4	...
SE	4.2	4.9	2.4	1.6	5.1	SE	2.2	3.0	2.7	0.2	3.1	...
SSE		4.7		3.8	6.0	SSE		2.8		2.2	3.6	...
S	3.2	3.7	5.9	5.5	6.6	S	1.8	2.1	3.8	3.8	4.3	...
SSW		2.2		6.3	6.7	SSW		1.1		4.9	4.9	...
SW	-0.2	0.4	5.9	6.2	6.1	SW	-1.7	-0.1	4.5	5.2	5.2	...
WSW		-1.5		5.1	5.3	WSW		-1.3		4.8	4.9	...
W	-3.4	-3.2	2.5	3.2	4.6	W	-1.6	-2.2	2.5	3.6	4.2	...
WNW		-4.4		0.9	4.5	WNW		-2.9		1.8	3.4	...
NW	-5.6	-4.9	-3.4	-1.6	5.1	NW	-2.2	-3.0	-1.7	-0.2	3.1	...
NNW		-4.7		-3.8	6.0	NNW		-2.8		-2.2	3.6	...
N	-2.4	-3.7	-5.9	-5.5	6.6	N	-2.8	-2.1	-4.5	-3.8	4.3	...
NNE		-2.2		-6.3	6.7	NNE		-1.1		-4.9	4.9	...
NE	0.3	-0.4	-5.5	-6.2	6.1	NE	0.1	0.1	-4.6	-5.2	5.2	...
ENE		1.5		-5.1	5.3	ENE		1.3		-4.8	4.9	...
Wind steady for at least 4 hours						**Wind steady for at least 24 hours**						
E	4.6	3.4	-1.5	-3.3	4.7	E	5.6	3.2	-1.7	-3.3	4.8	0.5
ESE		4.7		-0.8	4.8	ESE		4.8		-0.8	4.9	1.5
SE	5.4	5.3	2.3	1.8	5.6	SE	4.2	5.7	1.9	2.0	6.0	2.9
SSE		5.0		4.2	6.5	SSE		5.7		4.4	7.2	3.6
S	2.7	4.0	6.4	5.9	7.1	S	4.5	4.8	6.9	6.1	7.8	3.5
SSW		2.4		6.7	7.1	SSW		3.3		6.9	7.6	2.7
SW	0.1	0.4	5.8	6.4	6.5	SW	0.4	1.2	7.0	6.7	6.8	1.6
WSW		-1.5		5.2	5.5	WSW		-1.1		5.4	5.5	0.6
W	-4.2	-3.4	2.6	3.3	4.7	W	-3.6	-3.2	2.0	3.3	4.8	0.5
WNW		-4.7		0.8	4.8	WNW		-4.8		0.8	4.9	1.5
NW	-5.8	-5.3	-3.6	-1.8	5.6	NW	-6.5	-5.7	-3.6	-2.0	6.0	2.9
NNW		-5.0		-4.2	6.5	NNW		-5.7		-4.4	7.2	3.6
N	-2.5	-4.0	-6.7	-5.9	7.1	N	-4.0	-4.8	-6.6	-6.1	7.8	3.5
NNE		-2.4		-6.7	7.1	NNE		-3.3		-6.9	7.6	2.7
NE	-0.1	-0.4	-5.9	-6.4	6.5	NE	-0.3	-1.2	-6.0	-6.7	6.8	1.6
ENE		1.5		-5.2	5.5	ENE		1.1		-5.4	5.5	0.6

A--Increase over changing wind condition

The influence of the velocity of the generating wind--Figure 4 shows the wind current ellipses caused by winds of various strength blowing from different directions (magnetic) plotted from the components C_n of Table 4. Figure 4 shows that the major axis of the ellipse, that is, the strongest current, rotates from 9° for weak S winds, over 14° for median S×W winds to 28° for strong SSW winds. An explanation for this shift of the major axis of the wind current ellipse might be found in the following. The nearby coast is running S-N. It is therefore to be expected that currents along the E-W axis are not developing to the strength of N-S currents. The stronger the winds are the greater is the influence of the general circulation on the local situation. It had been found [MANDELBAUM, 1934, p. 50] that at Borkum Riff Light Ship, the westernmost of the German light ships, the change from W to E current and vice versa does not occur at N and S winds, but at NW×N and SE×S winds, so that the strongest current runs at SW×W to the E and NE×E to the W (see also Fig. 11). This means that at SW winds the greatest amount of water is coming in from the west into the German Bight which upon reaching the inner corner of the Bight has to flow N along the coast of Holstein. The current at Amrum Bank will, therefore, show a marked increase in velocity at SW-wind conditions in the German Bight, especially at strong wind velocities. The local trend for strongest current at S-N winds is overlain by the general trend for strongest current at SW-NE winds, with a resultant direction of the major axis of the current ellipse to 28° at strong SSW winds.

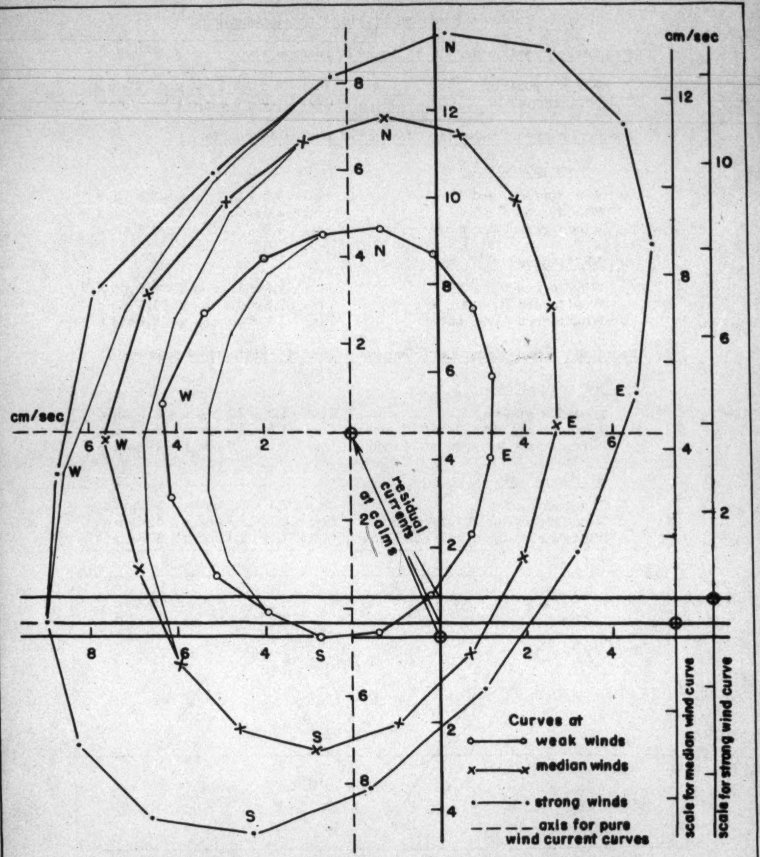

Fig. 4--Residual currents at various wind velocities (magnetic directions)

In Figure 5 are plotted the differences in degrees between the direction of the wind current and the direction of the generating wind, taken from the last column of Table 4. Deviation of the current to the right of the direction into which the wind is blowing is given as positive. The curves show the following facts: (1) The current sets in general to the right of the direction into which the wind blows, owing to Coriolis force. (2) The angle of deviation is small, as is to be expected in shallow waters, and reaches its maximum of about 20° at SE and NW winds. (3) With onshore winds from SSW to W×N the current runs for median and strong wind to the left of the generating wind. These interesting results are in complete agreement with the theoretical calculation of EKMAN [1906]: "In shallow waters near the coast the deviation of the current from the wind is relatively small and for onshore wind even contra solem."

Table 6--Functions f (x) for various conditions

Residual currents under the influence of average winds

NW components $f(x) = 4.6 + 3.2 \cos x + 3.8 \sin x$
NE components $f(x) = 1.9 - 3.2 \cos x + 5.5 \sin x$

Residual currents under the influence of wind of varying force

NW components

Wind forces 1 and 2: $f(x) = 4.8 + 2.7 \cos x + 2.8 \sin x$
Wind forces 3 and 4: $f(x) = 4.4 + 3.2 \cos x + 4.5 \sin x$
Wind forces 5 and more: $f(x) = 4.0 + 4.1 \cos x + 4.8 \sin x$

NE components

Wind forces 1 and 2: $f(x) = 1.9 - 1.9 \cos x + 3.8 \sin x$
Wind forces 3 and 4: $f(x) = 1.8 - 3.4 \cos x + 5.8 \sin x$
Wind forces 5 and more: $f(x) = 1.2 - 5.3 \cos x + 8.1 \sin x$

Residual currents under the influence of wind of increasing steadiness

NW components

Changing winds: $f(x) = 5.3 + 2.2 \cos x + 2.1 \sin x$
Winds steady for at least 4 hours: $f(x) = 4.5 + 3.4 \cos x + 4.0 \sin x$
Winds steady for at least 24 hours: $f(x) = 3.9 + 3.2 \cos x + 4.8 \sin x$

NE components

Changing winds: $f(x) = 2.1 - 3.6 \cos x + 3.8 \sin x$
Winds steady for at least 4 hours: $f(x) = 2.1 - 3.3 \cos x + 5.9 \sin x$
Winds steady for at least 24 hours: $f(x) = 1.6 - 3.3 \cos x + 6.1 \sin x$

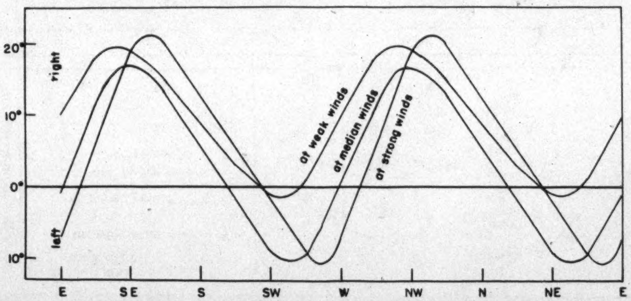

Fig. 5--Deviation of residual current from wind direction

It stands to reason that offshore winds will more easily produce currents into their directions than onshore winds. This fact is, of course, suppressed by the least square method used for calculating a best-fitting curve. In Figure 6 are presented also curves of the velocity of the wind currents plotted against wind direction taken from the calculated current ellipses. In Figure 7 the calculated velocity values for E and W winds taken from these curves are compared with the original values D_n upon which this calculation was based. For offshore currents at E-wind the original values are higher than the smoothed values for all wind velocities, 33 pct at weak winds, 17 pct for median winds, and 8 pct for strong winds. For onshore currents at W-winds the smoothed values are in fair agreement with the original values. It might be therefore advisable to correct the calculated current ellipses so as to take into account the asymmetry between offshore and onshore sides. Such empirically corrected values, entered in the last column of Table 4, are plotted in Figure 4.

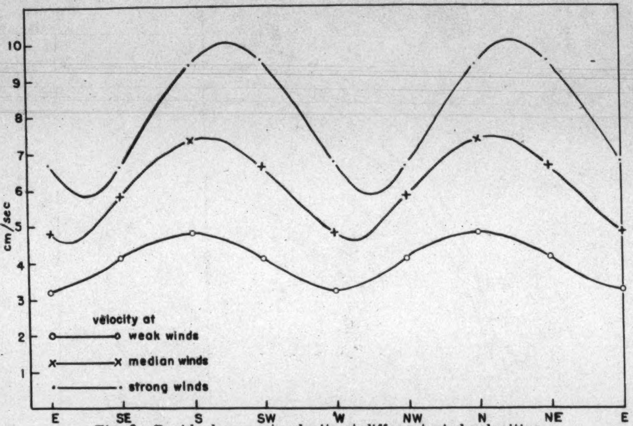

Fig. 6--Residual current velocity at different wind velocities

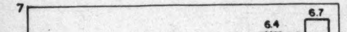

Fig. 7--Fitted values of current velocities compared with original values (currents at E- and W-winds)

The greatest velocities of the wind-generated residual currents are: 4.8 cm/sec for wind forces 1 and 2; 7.3 cm/sec for wind forces 3 and 4; and 10.0 cm/sec for wind forces 5 and more. This is roughly a ratio 1/1.5/2. These ratios fit well into previously established relationship at Borkum Riff [MANDELBAUM, 1934, p. 53] where a ratio 1/1.7 was found between the velocity of current generated by wind forces 1 to 3 and that of current generated by wind forces 4 and more. For currents in westerly direction, if we use the corrected values of the last column of Table 4 as a basis, the ratio is roughly 1/1.3/1.5. This depression of the ratio is caused by the fact that stronger winds need larger fetch to develop correspondingly strong currents. The proximity of the coast does not provide sufficient fetch for strong currents at strong winds. Their development is therefore unduly suppressed.

Influence of the steadiness of the generating wind--In Figure 8 are plotted the ellipses of the current generated by winds of various degrees of steadiness based upon the smoothed values C_n tabulated in Table 5. Curves showing the velocity of the current under these different wind conditions are plotted in Figure 9. For winds blowing from ENE-E and WSW-W, there is only a small increase in velocity with increase of the steadiness of the wind. However, for winds blowing from SE and NW to N, the velocity is nearly twice as large at steadily blowing winds than at changing wind directions (see also last part of Table 5, last column). The curves for currents at winds blowing steadily for four and 24 hours respectively show a greatest difference for wind with N and S components, with a maximum increase of 1.2 cm/sec at N and S winds, an increase of about 20 pct. The difference of the NW and NE component of Table 5, second and last parts ('24 hours' minus 'change'), were used to plot the 'pile-up currents' in Figure 10. The remarkable feature of this

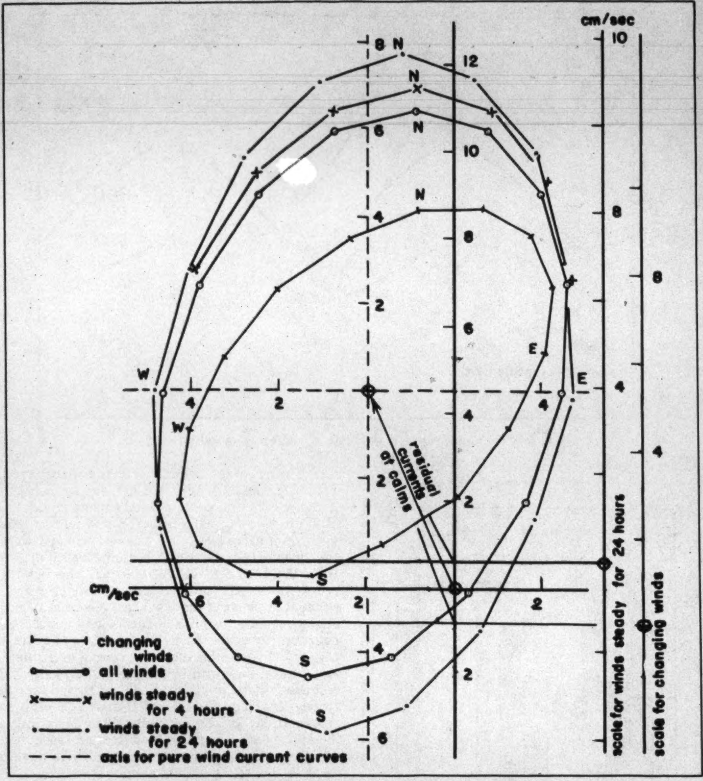

Fig. 8--Residual currents at winds of various steadiness

curve is that the 'pile-up current' sets N 17° W true, nearly the direction of the average residual current R (M_n). This result seems strange if we expect it to be a pile-up effect at steadily blowing winds. This effect should be greatest at offshore and onshore winds, that is, W and E winds, especially in such shallow waters as are found at this coast. We have to draw therefore the following conclusion: The consequence of steadily blowing winds in the German Bight is the strengthening of the general water transport along the coast in a northerly or southerly direction. Steadily blowing winds with northerly or southerly components will increase the velocity of this general circulation, for N winds clockwise and for S winds counter clockwise.

The actual residual currents at various wind situations--In order to obtain a picture of the actual currents at various wind situations, the wind-generated currents and the 'residual currents at calms' had to be considered combined. In Figures 4 and 8 coordinate axes in the N-S and E-W directions are drawn through the end points of the residual current vectors taken from Tables 1 and 2. For the purpose of simplifying the situation the same N-S axis is used for the six curves of Figures 4 and 8 since the difference in the E-W coordinates of the residual current vectors is insignificant. In Table 7 the velocity of the actual residual currents at various wind situations

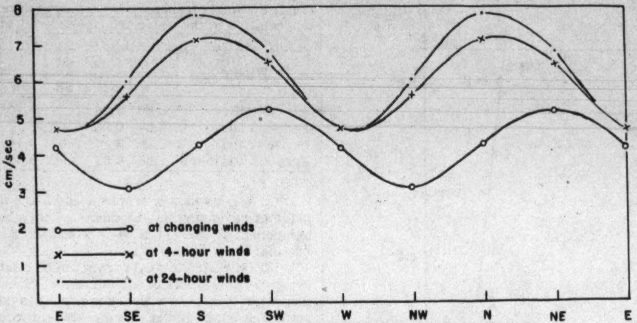

Fig. 9--Residual current velocity at changing and steady winds

Table 7--Velocity of the residual current at various wind situations

Wind direction	Wind force (Beaufort)					
	1 and 2		3 and 4		5 and more	
	v[a]	d[a]	v[a]	d[a]	v[a]	d[a]
	cm/sec	°	cm/sec	°	cm/sec	°
E	8.3	310	8.7	299	9.2	288
ESE	9.2	324	10.0	319	10.5	312
SE	9.5	335	10.7	333	11.0	332
SSE	9.6	344	11.4	345	12.1	349
S	9.4	352	11.6	354	12.9	1
SSW	8.8	359	11.2	3	12.9	12
SW	7.6	6	9.9	11	11.7	22
WSW	6.1	12	7.8	20	9.6	32
W	4.3	17	5.3	31	6.6	44
WNW	2.5	19	2.5	52	3.4	72
NW	1.0	353	1.0	132	2.3	151
NNW	1.4	273	2.5	201	4.6	200
N	2.7	270	4.0	226	6.9	218
NNE	4.0	278	5.2	242	8.3	233
NE	5.3	285	6.0	261	9.0	248
ENE	6.9	297	7.0	280	9.0	267

[a] Corrected values of magnitude and direction used.

Table 8--Water transport into four quadrants

Winds	Quadrant				Total	Transport components			
	NW	NE	SE	SW		N	W	S	E
All velocities	0.66	0.24	. . .	0.10	1.00	0.90	0.76	0.10	0.24
Forces 1 and 2	0.88	0.12	. . .	. . .	1.00	1.00	0.88	. . .	0.12
Forces 3 and 4	0.67	0.21	0.01	0.11	1.00	0.88	0.78	0.12	0.22
Forces 5 and more	0.47	0.29	0.02	0.22	1.00	0.76	0.69	0.24	0.31

are tabulated. The areas cut off by the coordinate axes from the current ellipses in Figure 4 were found by integration and their relative sizes presented in Tables 8 and 9. They indicate the water transport into the four quadrants under various wind conditions. From Table 8 the following pertinent facts can be read.

(1) The residual current has a strong northerly tendency that 90 pct of the currents at all wind situations have N-components.

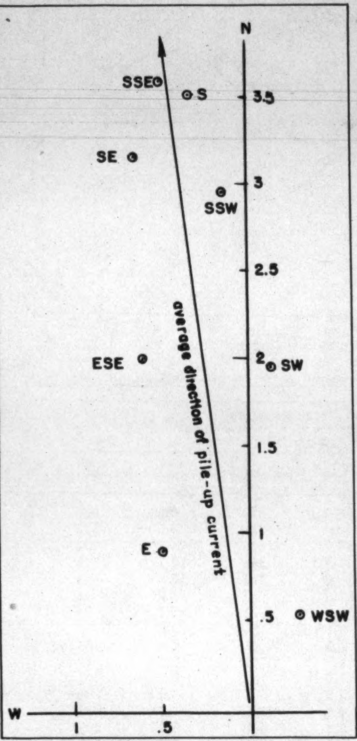

Fig. 10--'Pile-up' current

Table 9--Water transport at various wind velocities relative to the water transport at all winds

Winds	Quadrant				Total
	NW	NE	SE	SW	
All velocities	0.66	0.24	. . .	0.10	1.00
Forces 1 and 2	0.58	0.08	. . .	. . .	0.66
Forces 3 and 4	0.88	0.27	0.01	0.14	1.30
Forces 5 and more	1.00	0.62	0.05	0.46	2.13

(2) Weak winds of forces 1 and 2 are not capable of reversing this tendency. There is no S-component of current at weak winds from any direction.

(3) Only strong winds from the N-quadrant cause S-components of the currents. Even so, the water transport with S-component is only 24 pct of the total even at stormy winds (forces 5 and more). The greatest S-components are caused by N-winds. They are only 2.9 cm/sec for median winds and 5.4 cm/sec for strong wind as compared to N-components at S-winds which are even for weak wind 9.3 cm/sec and 12.9 cm/sec for strong winds (taken from Fig. 4).

(4) There are practically no residual currents into the S-E quadrant. Only two per cent even of the strongest winds cause water transportation into this sector.

(5) Only winds out of the sector SW to NW, and only strong ones, cause any significant E-components of the current (see Fig. 4).

(6) Although the average residual current $R(M_n)$ has only a small component to the W (due to the predominant wind direction SW in the German Bight), the currents under the influence of prevailing winds have strong westerly components. The water transport to the W is 76 pct. Westerly components are largest for E and ENE winds ranging from 5.3 cm/sec at weak winds to 9.0 cm/sec at strong winds as compared to the largest values of the E-component of the current of 1.3 cm/sec and 5.0 cm/sec at weak and strong winds respectively blowing from W and WSW.

Whether this may be construed as an indication of the existence of a separate eddy of the residual current in the German Bight will be discussed in the last paragraph.

The size of the total water transport at various wind velocities relative to each other can also be used to determine the current velocities caused by different wind velocities. The total water transport at wind forces 1 and 2, 3 and 4, and 5 and more are 0.66, 1.30, and 2.13 respectively, if we take the total water transport at wind of all velocities as the unit of comparison (Table 9). This is a ratio of roughly 1/2/3.3. Since the water transport is two dimensional, we have to take the square root of these ratios, to get one-dimensional velocities. These are $1/\sqrt{2}/\sqrt{3.3}$ = 1/1.4/1.8 which are somewhat smaller than those calculated on the basis of the greatest velocities of pure wind currents, which were found to be 1/1.5/2. The present ratio is that of the actual currents under the influence of winds based not on maximum but upon all current velocities.

Current circulation in the German Bight--The detailed picture of the rest current situation at Amrum Bank gained in this study together with that at Borkum Riff is well suited to piece together a picture of the current circulation in the German Bight as a whole. Borkum Riff is the westernmost German light ship station, Amrum Bank the northernmost. The current at Borkum Riff can be considered typical for the W-E current along the southern shore of the Bight and the current at Amrum Bank for that along the eastern shore with a main direction S-N.

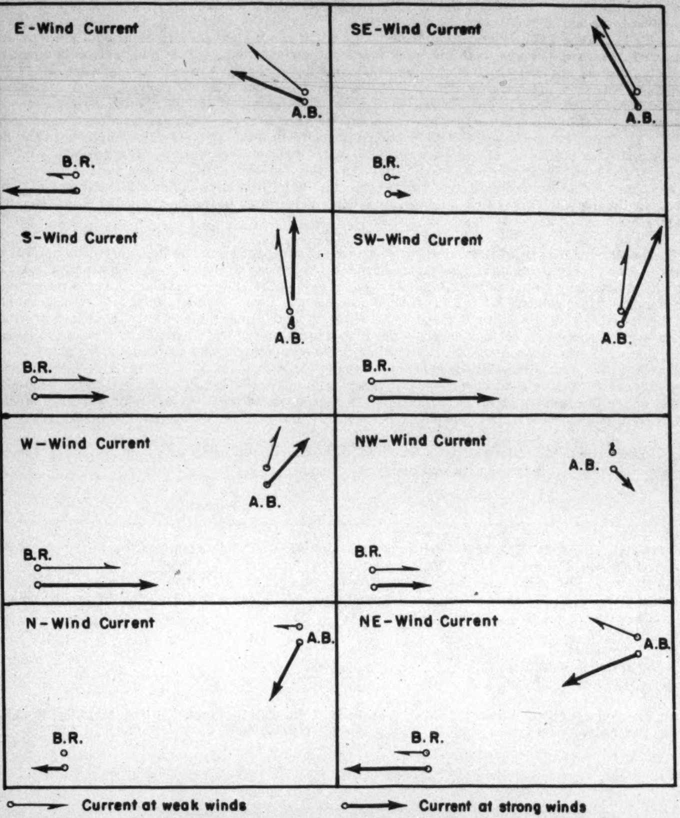
E-Wind Current
A.B.
B.R.
SE-Wind Current
A.B.
B.R.
S-Wind Current
A.B.
B.R.
SW-Wind Current
A.B.
B.R.
W-Wind Current
A.B.
B.R.
NW-Wind Current
A.B.
B.R.
N-Wind Current
A.B.
B.R.
NE-Wind Current
A.B.
B.R.
Current at weak winds
Current at strong winds

Fig. 11--Current circulation in the German Bight for winds from eight different directions; A. B. - Amrum Bank; B. R. - Borkum Riff

Even without detailed knowledge of the current situation at stations in between, we gain a good picture of the general current circulation inside the German Bight.

(1) The average residual current at Borkum Riff has a velocity of 4.3 cm/sec to the east, which is somewhat smaller than that at Amrum Bank of 5.1 cm/sec to the north.

(2) The residual current at calms for strong wind at Borkum Riff, however, is only 2.3 cm/sec, a reduction of nearly 50 pct from the average residual current. At Amrum Bank the comparable values are 5.1 cm/sec and 4.2 cm/sec, a reduction of only 17.5 pct. For Borkum Riff no information about the influence of wind steadiness was calculated, however, 'strong' winds in the calculation of the currents at Borkum Riff include those of force 4. The conclusion seems, therefore, to be justified that at Amrum Bank much stronger causes -- winds excluded -- are responsible for residual current than at Borkum Riff. One of the causes might be the large volume of fresh water

brought into the German Bight by the Elbe and Weser which would accordingly take a path to the N along the coast of Holstein.

(3) In Figure 11 the residual current under winds from eight directions at both stations are entered as on small maps, both for weak winds and strong winds. (This comparison is quantitatively not quite correct since at Borkum Riff, winds of forces 1-3 were taken as weak winds and winds of forces 4 and more as strong winds, while at Amrum Bank the corresponding forces are 1 and 2 and 5 and more.) The arrows show at S-, SW-, and W-winds steady and strong currents along the coast in a counter-clockwise fashion. At SE winds the W-E current along the southern shore is rather insignificant and the northern branch has a strong westerly component. The development of a clockwise circulation along the coast can be recognized at strong winds from N and NE. At E winds no circulation is indicated. The water at both stations flows westward. At strong NW winds we find according to these maps the only situation where the residual currents at both stations oppose each other and would cause a pile-up of water in the mouth of the Elbe. Significantly, both currents have small velocities.

The driving force of the wind is the strongest of all forces causing non-periodic residual currents. The problem, whether a separate current eddy exists in the German Bight and where its northern boundary lies, has meaning only if we consider the actual residual currents influenced by the prevailing winds. Although the residual currents have a strong westerly tendency, as shown at the discussion of the water transport, the detailed analysis of the current circulation at winds from eight different directions does not show an indication for the existence of a separate eddy. At those wind situations where a counter-clockwise movement of the water develops along the coast (S-, SW-, and W-winds) the current sets north at Amrum Bank. If a separate eddy exists under these favorable wind conditions, its boundaries must lie farther north. At those wind situations where the current at Amrum Bank sets in a pronounced north-westerly or westerly direction (NE-, E-, and SE-winds), the current at Borkum Riff either is insignificant or sets W.

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EFFECT OF WESTERN DROUGHT ON THE WATER RESOURCES OF SAFFORD VALLEY, ARIZONA, 1940-1952

R. L. Cushman and L. C. Halpenny

(Publication authorized by the Director, U. S. Geological Survey)

__Abstract__--Records of precipitation, runoff in the Gila River, ground-water withdrawals for irrigation, and changes in ground-water level in Safford Valley, Arizona, provide a basis for noting the effect of wet and dry periods on the hydrologic cycle. An unusually wet period, 1940-1941, was followed by a period of drought, 1942-1952. The irrigable area is limited by natural causes, the area irrigated with surface water is effectively limited by court decree, and less than 1000 acres are irrigated exclusively from wells. Thus relatively little expansion in this irrigated area has occurred during the period concerned to obscure the climatic effects, although cultivation has been more intensive in recent years and the water demand has been correspondingly larger. The wet period of above-normal stream flow and ground-water levels provided a cushion that delayed and reduced the effects of the drought. As the ground-water storage in the valley is relatively small, however, withdrawals of ground water as a supplemental supply for irrigation eventually lowered water levels sufficiently to reduce well yields. The concentration of dissolved mineral matter increased in the remaining ground water, making it less desirable for irrigation use than previously.

__Introduction__--The drought conditions that have prevailed for several years in the southwestern part of the United States have been the subject of much discussion. Opinions differ on the intensity of the drought and on its effect upon the economy of the region. In Arizona the effects of the drought upon the water supply for irrigation are difficult to evaluate, for the dry years coincided with a period of high prices for crops and the irrigated acreage in most areas was enlarged in spite of the unfavorable climatic conditions.

In Safford Valley, Arizona (Fig. 1), however, the total area irrigated has remained practically constant since 1920, although in recent years the intensity of cultivation and the total water need have increased somewhat. Thus the effects of wet and dry periods on the hydrologic cycle can be noted more readily here than in many other areas.

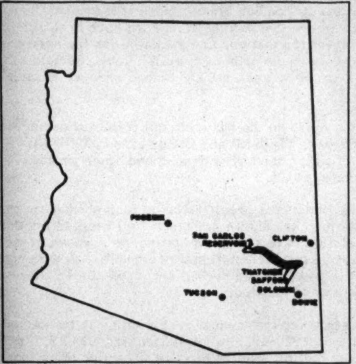

Fig. 1--Map of Arizona showing location of Safford Valley

__Geologic and hydrologic setting__--Safford Valley is in the Mexican Highland section of the Basin and Range Province of the United States [FENNEMAN, 1931]. The valley is bordered on the northeast by the Gila Mountains and on the southwest by the Pinaleno, Santa Teresa, and Turnbull Mountains. The valley appears to be of the fault-block type and contains a thickness of more than 3000 ft of alluvial fill consisting of boulders, gravel, sand, silt, and clay, and occasional beds and lenses of caliche. The axis of the valley is occupied largely by lake-bed clay which is, at least in the upper part, of Pleistocene age.

Erosion by the Gila River subsequent to deposition of most of the alluvial fill has cut an inner valley about two miles wide and about 150 ft deep. This inner valley has been nearly refilled with gravel, sand, and silt of Recent age. The floor of the inner valley is fairly level and constitutes practically the only land in the valley that is suitable for irrigation.

The ground water of the inner valley is derived from four principal sources: (1) spring flow and upward seepage from the older alluvial fill, (2) underflow of Gila River and tributary washes, (3) recharge from the Gila River when the river is flowing and the water table is below the level of the river, and (4) infiltration from rainfall and from irrigation water in canals and on fields. Of these, the last item is of greatest importance. The ground water is discharged by pumping and by natural means. Natural discharge occurs by transpiration and evaporation in the part of the area occupied by phreatophytes, by evaporation from bare wet land surfaces in the bottom land, by underflow out of the valley along Gila River, and by seepage from the ground-water reservoir into the river. Natural discharge by phreatophytes in 1944 was about 50,000 to 60,000 ac ft, estimated on basis of quantitative data for the lower part of the valley [GATEWOOD and Others, 1950].

The Gila River in the valley flows most of the year but is dry in places early each summer and fall. Irrigation from the river began about 1865 and, by 1920, about 32,500 acres was under cultivation [DUNGAN, 1953]. There has been practically no change in the area irrigated in the past 30 years.

Downstream users of water, largely Indians, began to note depletion of stream flow in the Gila River early in the period of development of irrigation in Safford Valley, and a long series of legal arguments resulted. In 1929 Coolidge Dam was built at the lower end of Safford Valley to impound water for irrigation by the downstream users. In 1935 a court order [U. S. DISTRICT COURT, 1935] adjudicated waters of the Gila River between users of water in areas upstream and downstream from the dam.

About 1930 some farmers began using ground water as a supplemental supply for irrigation water during seasons of low river flow. By 1940 about 150 irrigation wells were being operated, and by 1945, about 300. In 1952, 513 wells were used for irrigation.

Data available--Stream-flow records are collected on the Gila River at the upper end of Safford Valley, at Safford, and at the head of San Carlos Reservoir, on San Simon Creek at the mouth, and on all canals at their headings. Records of ground water withdrawn for irrigation have been collected for each year since 1940. Records of water-level fluctuations are available for the period 1940-1952. The quality of the waters of the valley has been described by HEM [1950]. Periodic resampling of well and river waters provides data relating to seasonal and annual changes in their quality.

A water inventory for parts of 1940 and 1941 was made on the basis of data collected during the intensive phases of the work by the Geological Survey [TURNER and Others, 1941; TURNER and HALPENNY, 1941]. An intensive investigation of water used by saltcedar and other phreatophytes was made in 1943-1944 [GATEWOOD and Others, 1950].

Climatological data--Figure 2 shows graphically the annual precipitation at four stations in the vicinity of Safford Valley. The locations of these stations are shown in Figure 1. Precipitation data are shown for the entire period of record for each station to assist in evaluating the dryness or wetness of the period 1940-1952. The average precipitation for each station was computed as the average for the entire period of the record. Breaks in the precipitation record occurred at all stations. Short breaks were interpolated but missing full years were omitted.

Analyzing the graphs by ten-year periods, it is observed that annual precipitation in the period 1900-1909 ranged about two inches above the average; in 1920-1929 precipitation was about 2.5 inche below the average; in 1930-1939 it was about average; and in 1940-1949 it was a fraction of an inch below the average. Passing over the two unusually wet years 1940 and 1941, the annual precipitatio for the ten-year period 1942-1952 was about two inches below the average. In general, precipitation was above average from 1900 to 1920 and below average from 1920 to 1953. For Safford Valley, the impression is gained that a gradual but not a uniform decrease in precipitation occurred through the period 1900-1952 and that, by comparison, the dry period 1942-1952 was perhaps not as severe as might have been thought previously.

Stream flow--Variations in the amounts of annual precipitation are reflected to a degree in the discharge of the Gila River. A summary of the annual discharge of the Gila River at the Solomon gaging station, at the upper end of Safford Valley, is shown graphically in Figure 3. Complete calendar-year records of the discharge of the Gila River at this station are available only for the period 1915-1952. Although the stream-flow data do not cover as long a period as do the precipitation data, the record is adequate to establish the flow pattern prior to and during the period 1940-1952.

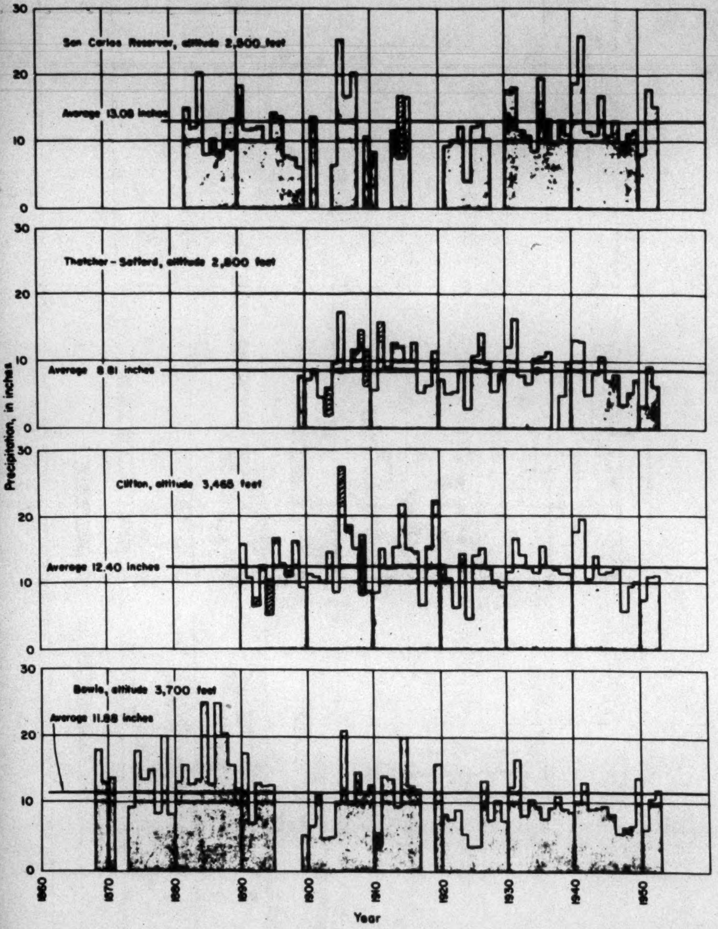

Fig. 2--Precipitation at stations in vicinity of Safford Valley, Graham and Cochise Counties, Arizona (cross hatching indicates interpolation for periods of missing record)

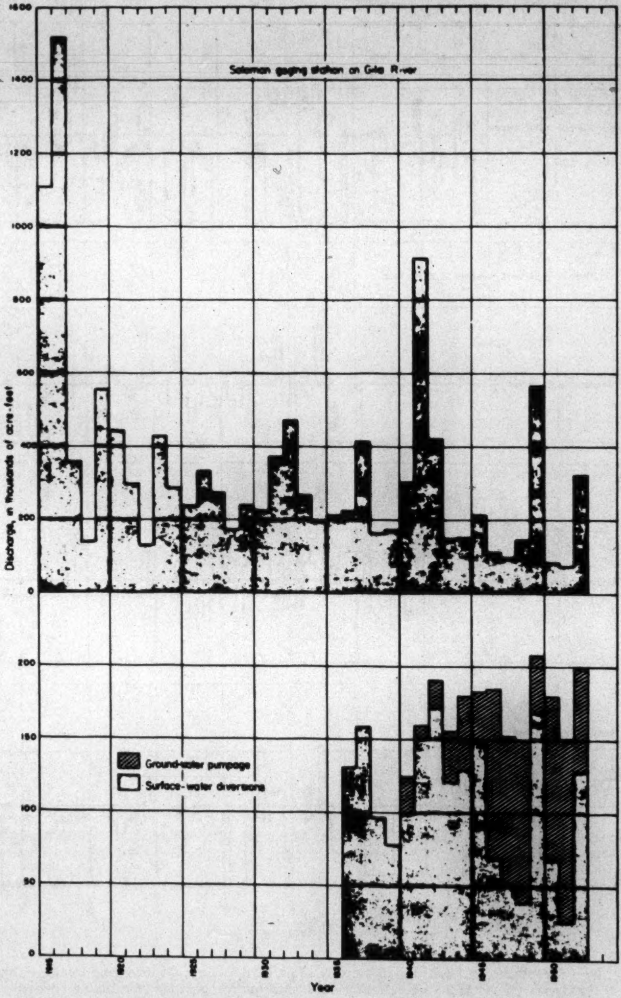

Fig. 3--Discharge of Gila River at Solomon, Arizona, and combined surface-water diversions and ground-water pumpage, Safford Valley

A downward trend in the annual discharge of the Gila River is observable in the graph in Figure 3. The high discharges became progressively lower and the low discharges also became progressively lower as the years of decreasing precipitation advanced. Ground-water reservoirs upstream that maintained the base flow in the Gila River were partially depleted, owing to the reduction in recharge and the increased discharge by evapotranspiration and pumping from wells that resulted directly or indirectly from the reduction in precipitation. As water levels declined in these ground-water basins, so did the amount of water these reservoirs contributed to the base flow. A similar downward trend in runoff apparently exists also in other streams in Arizona. Studies on the Salt River above Roosevelt Dam indicate that there has been less runoff for the same precipitation since 1928 than before (J. S. Gatewood, personal communication, 1954). No reason has been found yet to explain the decrease.

Ground-water supply--What has been the effect of the below-normal precipitation and the declining annual flow of the Gila River on the ground-water resources of Safford Valley? Although the total acreage irrigated has not increased appreciably since 1920, favorable economic conditions have led to more intensive cultivation of the lands, and hence the total supply of water needed for irrigation has increased. Figure 3 includes a graph showing the combined ground-water pumpage and surface-water diversions since 1940. The annual sums of these components range from 150,000 to about 200,000 ac ft. The changes in quantity of water used from year to year result from several factors, including timeliness of rains during the irrigation season, type and number of crops grown each year, and extent to which the ground-water supply was replenished by heavy application of surface water when available.

Pumping from wells increased greatly during the period 1940-1952, and in some years it provided the largest share of the irrigation water. The largest amount pumped in any one year was 125,000 ac ft in 1951, but in four other years (1946, 1947, 1948, and 1950) the pumpage was in excess of 100,000 ac ft. In those five years of greatest pumping, water withdrawn from wells supplied about 65 to 80 pct of the irrigation supply. In spite of the large volumes of water pumped in 1947, 1948, and 1951, many acres of crops suffered for lack of water because wells and stream flow together were inadequate to supply all that was needed. The yield of the wells was inadequate because of the decrease in rate of yield per well resulting from the dewatering of one-third to one-half the total thickness of the aquifer in the Recent fill. To make up for the decrease in yield per well, more wells were drilled. Eventually the spacing of wells became such that considerable interference between wells developed, and the rate of yield per well decreased more. Wells that formerly produced as much as 2000 gpm (gallons per minute) dropped in yield to 1000 gpm or less. Wells that did not decrease in yield by at least 50 pct were the exception rather than the rule. Deepening the wells to increase yield was not an answer because, when they were drilled, most of the wells penetrated the entire 125 ft or so of the Recent fill, and the older fill below is relatively unproductive.

Fluctuations of the water table in the period 1940-1952 differed from place to place in the valley, depending on local factors. Near the Gila River the water table fluctuates in response to changes in stage of the river flow. Prior to the heavy pumping of ground water in Safford Valley, the Gila River was perennial and the water table intersected the channel of the river, resulting in a mutual interchange of water between the river and the ground-water reservoir. During high stages of flow in the river, the ground-water reservoir received some recharge; during periods of low flow, the direction of movement was reversed. In general, the effect of actual movement of water from the river into the ground-water reservoir does not extend more than a quarter of a mile away from the river, but the change in river stage may cause pressure effects in the ground-water reservoir that are reflected in wells more than a mile from the river. The effects of recharge to and discharge from the ground-water reservoir in the vicinity of the river caused by changing river stages in the period 1940-1952 are shown in the graphs of water-level fluctuations in wells (D-6-28)31aac, (D-6-25)27dcd, and (D-4-22)13ac (Fig. 4). All three wells are within half a mile of the river. The water levels in them show that the relative position of the water table with reference to the stage of the river is a factor in the interchange of water. In 1940 the ground-water levels were comparatively high, and the unusually large river flows in 1940-1941 (Fig. 3) raised the water levels in these wells only about three to five feet. In the winter of 1948 and the spring of 1949, the ground-water levels were five to ten feet lower than in 1940, and smaller river flows than in 1940-1941 raised the water levels in these wells two or three times as much as in 1941. This larger rise is attributed to the more favorable recharge conditions in the latter period. In 1940 the Gila River was perennial throughout the valley and relatively large river flows coursed through the channel, perhaps providing some recharge but in large measure flowing on top of an already saturated river bed. Between 1941 and 1948 the water table was lowered throughout the valley because of the drought and heavy pumping. The water table no longer intersected the river channel everywhere in the valley, and in most places it was several feet below the river channel. The river flows of 1948-1949

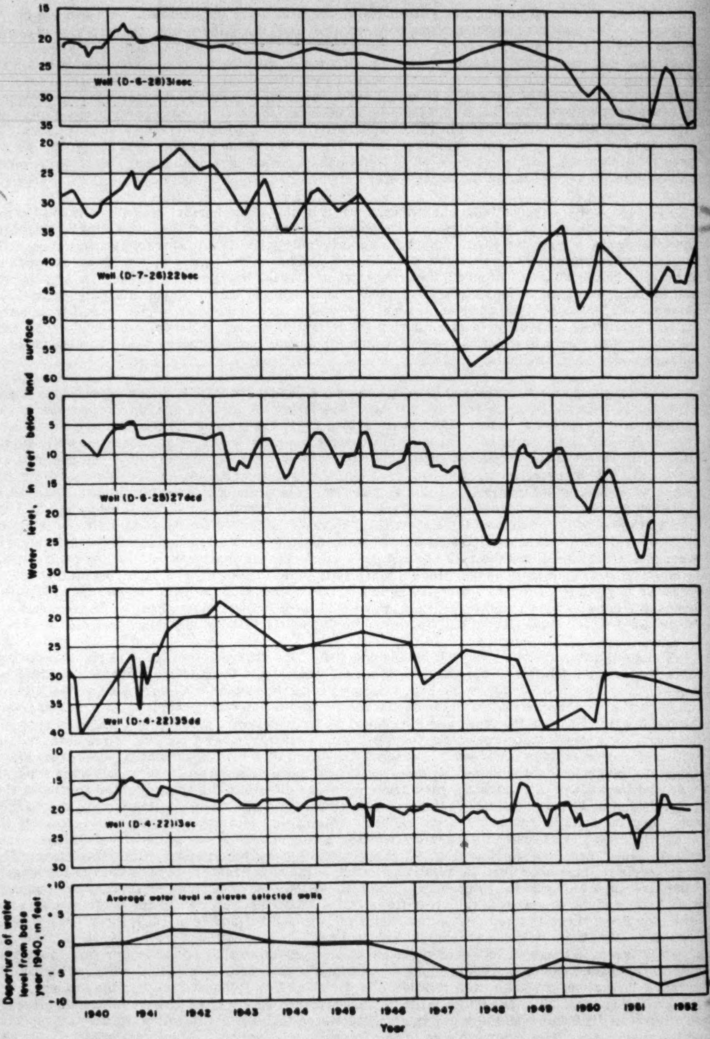

Fig. 4--Water levels in wells in Safford Valley, Graham County, Arizona encountered dry stretches of river bed that offered excellent recharge areas, and a large volume of recharge occurred. Thus the drought that caused the water-table lowering near the river made it possible for the areas adjacent to the river to be more receptive to recharge.

Other beneficial effects occurred in the river-bottom areas during the period of low ground-water levels. Many of the phreatophytes in the river bottom were unable to deepen their root systems fast enough to keep up with the declining water table. The result was that the plants either died or became partially dormant, and their draft on the ground-water supply was greatly reduced.

In the irrigated areas of the Safford Valley a quarter of a mile or more from the river, the general direction of movement of ground water is from the sides of the valley toward the river. In this area, seepage losses from water in canals and from water applied to fields are the principal sources of recharge to the ground-water reservoir, and pumping from wells is the principal means of ground-water discharge. Investigations in the valley indicate that about half of all water diverted from the river and about a fourth of all water pumped from wells seeps downward to the water table [TURNER and Others, 1941].

A change either in the quantity of surface water used for irrigation or in the quantity pumped from wells will cause changes in the elevation of the water table beneath the irrigated area of the valley. The graph of water-level fluctuations in well (D-7-26)22bac (Fig. 4) is typical of water-table trends in the irrigated area and shows the magnitude of water-level changes in the most heavily pumped areas. The general water-level trend in this well is similar to that discernible in the water-level fluctuations in the three wells mentioned previously, that is, a rising water level in 1940 and 1941 (and in some places in 1942), an ensuing water-level decline interrupted in 1948-1949 by a rise, and a resumption of a general water-level decline. The two major differences between the fluctuations of the water table in areas near the river and those away from the river are: (1) the larger net declines occur in the areas away from the river; and (2) the gross declines caused by pumping during 1946-1948 and 1950-1951 are greater in the areas away from the river.

The effects of the wet and dry periods are also in evidence in the water levels in wells on the alluvial slopes between the mountains and the inner valley. Well (D-4-22)35dd (Fig. 4) is near one of the major washes tributary to the Gila River, and is about three miles upstream from the irrigated area and about eight miles downstream from the recharge area near the base of the Pinaleno Mountains. The well is equipped with a windmill, and the sharp downward breaks in the graphs represent intermittent pumping of the well. Recharge that occurred near the mountains in 1940-1941 took about two years to complete its journey of eight miles to the well. After the peak had passed, a general downward trend in water level prevailed throughout the balance of the period 1943-1952. The uniformity of the downward-trending water level attests to the constancy of drought conditions. The slow rate of movement of water from the recharge area near the mountains indicates that the effect of the drought will be felt in the valley to some extent for two or three years after the drought is over.

The graph at the bottom of Figure 4 shows departure, from the base year 1940, of the annual average water level in Safford Valley. This graph was based on records of 11 selected representative wells. In general, the average water level in the valley was about two feet higher in 1941 and 1942 than in the base year 1940; by 1943 the average level had returned to about that of the base year; and from 1944 through 1952 the average level was below the base level, reaching its lowest point of about 8.5 ft in 1951. This graph clearly shows a downward trend in Safford Valley's ground-water supplies for the latter two-thirds of the period 1940-1952.

Quality of the water supply--The ground waters in most parts of the Safford Valley are relatively highly mineralized. Water in the older fill, virtually untapped by irrigation wells, generally contains more than 14,000 ppm (parts per million) of dissolved solids. Waters in the Recent alluvium of the inner valley range in dissolved solids from about 500 ppm in local areas, such as near the mouths of the larger washes, to more than 5000 ppm. Dissolved mineral matter in most of the water in the Recent fill ranges from 1000 to 3000 ppm.

The chemical quality of the waters from the older alluvial fill has not changed appreciably in the period 1940-1952. Mineralization of the waters in the Recent fill has increased noticeably but not uniformly throughout the valley. The surface flow of the river normally is of relatively low mineralization, and the use of large quantities of river water for irrigation tends to reduce the mineral concentration in the ground water by removing some of the salts through return flow to the river. During the years when there was a shortage of surface water, large quantities of ground water were pumped, with the result that mineralization increased in the ground water. The increase is caused mainly by repumping and reuse of water that had been returned as downward seepage from canals and irrigated fields.

Comparison with other areas--In many parts of the Southwest the irrigated areas expanded throughout the period 1940-1952, and therefore the effects of the wet and dry cycles could not be detected as readily as in Safford Valley. In most of these other areas the volume of ground water in storage is much larger than in Safford Valley, and the ratio of annual withdrawals to total storage is lower. However, many of these other areas have no surface-water supply, so that not only is the draft on ground water relatively great but no surface water is available for recharge.

Conclusions--Available records show that both precipitation and runoff have been generally less since 1920 than in the three or four decades prior to that year. Since 1942 they have been considerably less than the long-term averages. The result has been that more and more frequently the surface-water supply upon which irrigation in the valley originally depended has been inadequate. Ground-water supplies have been tapped to supplement the available surface water, and the long-range effect has been a lowering of the water table.

The period 1940-1941 was much wetter than average, and the period 1942-1952 was much drier than average. Stream flow was above normal during the wet period, and the water table was at a high stage. Since 1942 the effects of the drought have been aggravated because the demand for water was great owing to favorable economic conditions. The immediate effect of the drought was a decline in runoff and an increase in ground-water withdrawals. In spite of partial replenishment of the ground-water supply seasonally, the water table has trended gradually downward. The result has been that well yields have declined, and more wells have had to be drilled to provide the needed water. When the water table is low, the ground-water supply contains a greater proportion of dissolved mineral matter and hence is less desirable for irrigation.

Even when the drought terminates, the slow rate at which recharge moves from the mountain areas to the irrigated inner valley will cause some effects of the drought to persist for two or three years.

In addition to the adverse effects, the lowering of the water table in Safford Valley in recent years has resulted in two advantages so far as the valley is concerned: (1) the dry river bed provided greater opportunity for recharge than when perennial flow occurred in the river; and (2) the large waste of ground water by phreatophytes in the river bottom has been reduced.

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NON-STEADY RADIAL FLOW IN AN INFINITE LEAKY AQUIFER

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Abstract--The non-steady drawdown distribution near a well discharging from an infinite leaky aquifer is presented. Variation of drawdown with time and distance caused by a well of constant discharge in confined sand of uniform thickness and uniform permeability is obtained. The discharge is supplied by the reduction of storage through expansion of the water and the concomitant compression of the sand, and also by leakage through the confining bed. The leakage is assumed to be at a rate proportional to the drawdown at any point. Storage of water in the confining bed is neglected. Two forms of the solution are developed. One is suitable for computation for large values of time and the other suitable for small values of time. This solution is compared with earlier solutions for slightly different boundary conditions.

Introduction--The differential equation for radial flow in an elastic artesian aquifer with linear leakage has been given by JACOB [1946]. He also obtained the non-steady drawdown distribution produced by a well of constant discharge situated in the center of a circular region whose outer boundary is maintained at constant head. The head distribution in his problem is initially uniform.

In this paper the solution is obtained for the problem in which the outer boundary is removed to infinity.

Statement of the problem--The problem is to determine the variation with time of the drawdown induced by a well steadily discharging from an infinite leaky aquifer in which the initial head is uniform. Leakage into the aquifer is assumed vertical and proportional to the drawdown. Stated mathematically the boundary-value problem is

$$\partial^2 s/\partial r^2 + (1/r)\, \partial s/\partial r - s/B^2 = (S/T)\, \partial s/\partial t \quad \ldots\ldots\ldots\ldots\ldots (1)$$

$$s(r, 0) = 0 \qquad r \geq 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2a)$$

$$s(\infty, t) = 0 \qquad t \geq 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2b)$$

$$\lim_{r \to 0} r\, \partial s(r, t)/\partial r = -Q/2\pi T \qquad t > 0 \quad \ldots\ldots\ldots\ldots\ldots (2c)$$

where

$s(r, t)$ is the drawdown at any time and any distance from the well.
r is the distance to any point measured from the axis of the well.
S is the storage coefficient of the artesian aquifer (a non-dimensional constant) defined as 'the product of the thickness of the artesian bed and the relative volume of water released from storage by a unit decline of head' [JACOB, 1946].
K and K' are the hydraulic conductivities (or 'permeabilities') of the artesian sand and confining bed, respectively. They have the dimension L/t.
b and b' are the thicknesses of the artesian sand and confining bed, respectively.
$T = Kb$ is the transmissibility (of dimension L^2/t) of the artesian sand. The ratio K'/b' may be termed 'specific leakage' or leakance [HANTUSH, 1949, p. 8]. It has the dimension $1/t$. The transmissibility divided by the leakance (of dimension L^2) is symbolized by B^2.
Q is the discharge of the well.

Solution of the problem--After separating the variables, it can be shown that

$$J_0(\alpha r/B) \exp[-(\alpha^2 + 1)\, Tt/SB^2] \quad \text{and} \quad K_0(r/B)$$

are particular solutions of (1), where J_0 and K_0 are respectively the Bessel function of the first kind of zero order and the modified Bessel function of the second kind of zero order, and where α is any real constant.

Due to the linearity and homogeneity of (1), the above particular solutions can be combined linearly to obtain the following solution

$$s = c\left[\int_0^\infty A(\alpha)\, J_0(\alpha r/B)\, \exp\left[-(\alpha^2+1)\, Tt/SB^2\right] d\alpha + K_0(r/B)\right] \quad \ldots\ldots\ldots \quad (3)$$

in which c is an arbitrary constant, and in which $A(\alpha)$ is a function depending upon α alone and hence constant or independent of the variables of (1).

That (3) satisfies condition (2b) is seen immediately. Recalling that

$$\lim_{r \to 0} K_0(r/B) = -0.5772 - \ln(r/2B)$$

and applying condition (2c), the value of c is found to be $Q/2\pi T$. The function $A(\alpha)$ may be found by using condition (2a) as follows. When $t = 0$, $s = 0$ and (3) becomes

$$0 = K_0(r/B) + \int_0^\infty A(\alpha)\, J_0(\alpha r/B)\, d\alpha \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

Using the integral relation [WATSON, 1944, p. 425]

$$K_0(r/B) = \int_0^\infty [\alpha/(\alpha^2+1)]\, J_0(\alpha r/B)\, d\alpha$$

Eq. (4) reduces to

$$\int_0^\infty J_0(\alpha r/B)\, [A(\alpha) + \alpha/(\alpha^2+1)]\, d\alpha = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

whence

$$A(\alpha) = -\alpha/(\alpha^2+1)$$

Substituting the values of c and $A(\alpha)$ thus obtained, the formal solution of the problem is

$$s/(Q/2\pi T) = K_0(r/B) - \int_0^\infty [\alpha/(\alpha^2+1)]\, J_0(\alpha r/B)\, \exp[-p(\alpha^2+1)]\, d\alpha \quad \ldots\ldots \quad (6)$$

where

$$p = Tt/SB^2$$

As pumping continues indefinitely, that is, as $t \to \infty$, the integral in (6) becomes zero and the drawdown is represented by $s/(Q/2\pi T) = K_0(r/B)$, which is the steady-state solution of the problem [JACOB, 1946].

To evaluate the infinite integral of (6), hereafter represented by I, one proceeds as follows. The integral representation of $1/(\alpha^2+1)$ is

$$\int_0^\infty \exp[-(\alpha^2+1)\,x]\, dx$$

Thus, replacing $1/(\alpha^2+1)$ by its integral form and changing the order of integration, one obtains

$$I = \int_0^\infty \exp[-(p+x)]\, dx \int_0^\infty J_0(\alpha r/B)\, \exp[-(p+x)\,\alpha^2]\alpha\, d\alpha \quad \ldots\ldots\ldots \quad (7)$$

Reversing the order of integration is justified, since the integral I is convergent [BROMWICH, 1947, p. 504]. Integration with respect to α gives [WATSON, 1944, p. 394]/

$$\int_0^\infty J_0(\alpha r/B) \exp[-(p+x)\alpha^2]\alpha \, d\alpha = [1/2(p+x)] \exp[-(r^2/B^2)/4(p+x)]$$

Hence, (7) becomes

$$I = (1/2)\int_0^\infty [1/(p+x)] \exp[-p-x-(r^2/B^2)/4(p+x)] \, dx$$

and upon the substitution of y for (p + x), it becomes

$$I = (1/2)\int_p^\infty (1/y) \exp[-y-(r^2/B^2)/4y] \, dy \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

If, in the integral of (8), $\exp[-r^2/4B^2y]$ is replaced by the absolutely and uniformly convergent series

$$\sum_{n=0}^{\infty} \frac{(-1)^n (r^2/4B^2)^n}{n!\, y^n}$$

and if the order of integration and summation are changed, integration by parts will result in

$$I = (1/2)\exp(-p) \sum_{n=1}^{\infty} \sum_{m=0}^{n-1} \frac{(-1)^{n+m}(n-m-1)!\,(r^2/4B^2)^n}{(n!)^2\, p^{n-m}}$$

$$+ (1/2)\int_p^\infty \left\{[\exp(-y)]/y\right\} dy \left[\sum_{n=0}^{\infty} \frac{(r/2B)^{2n}}{(n!)^2}\right]$$

$$I = -(1/2)\exp[-r^2/4B^2u] \sum_{n=0}^{\infty} \sum_{m=0}^{n} \frac{(-1)^{n+m}(n-m)!\,(r^2/4B^2)^m\, u^{n-m+1}}{(n+1)!^2}$$

$$+ (1/2)[-\mathrm{Ei}(-r^2/4B^2u)]\, I_0(r/B) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

where $I_0(r/B)$ is the modified Bessel function of the first kind and zero order, and where

$$u = r^2/4B^2p = r^2S/4Tt$$

That the series in (9) is uniformly and absolutely convergent can be seen by applying the ratio test for any given value of m. Because of the absolute and uniform convergence of this double series, then, summation in any manner is justified. Separating the first column m = 0 and the diagonal m = n from the double series, the series of (9) becomes

$$\sum_{n=0}^{\infty} \frac{(-1)^n u^{n+1}}{(n+1)\,(n+1)!} + \sum_{n=1}^{\infty} \frac{(r^2/4B^2)^n u}{(n+1)!^2} + \sum_{n=2}^{\infty} \sum_{m=1}^{n-1} \frac{(-1)^{n+m}(n-m)!}{(n+1)!^2} (r^2/4B^2)^m u^{n-m+1}$$

$$\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

Recognizing the first series in (10) as $0.5772 + \ln u + [-\mathrm{Ei}(-u)]$, and the second series as $-u + u[I_0(r/B) - 1]/(r^2/4B^2)$, and by changing the index of summation from n = 2 to n = 1 in the third series; and then substituting in (9), and then in (6), one obtains

$$s/(Q/4\pi T) = 2K_0(r/B) - I_0(r/B)\,[-Ei(-r^2/4B^2u)] + [\exp(-r^2/4B^2u)]\Big\{0.5772 + \ln u + [-Ei(-u)] - u + u\,[I_0(r/B) - 1]/(r^2/4B^2) - u^2 \sum_{n=1}^{\infty}\sum_{m=1}^{n} \frac{(-1)^{n+m}\,(n-m+1)!}{(n+2)!^2}\,(r^2/4B^2)^m\,u^{n-m}\Big\} \quad \ldots\ldots (11)$$

The series of (11) is rapidly convergent for the values $r/2B \leq 1$ and $u \leq 1$. Only a few terms are required to obtain results accurate to four decimal places. When $r/2B \leq 0.10$ and $u \leq 1$, the solution can be reduced to

$$s/(Q/4\pi T) = 2K_0(r/B) - I_0(r/B)\,[-Ei(-r^2/4B^2u)] + [\exp(-r^2/4B^2u)][0.5772 + \ln u + [-Ei(-u)] + (u/4)(r^2/4B^2)(1 - u/9)] \quad \ldots (12)$$

which gives values of the drawdown accurate to four decimal places.

For the range of values $r/2B \leq 0.10$ and $u \leq 0.10$, the solution may be approximated by

$$s/(Q/4\pi T) = 2K_0(r/B) - I_0(r/B)\,[-Ei(-r^2/4B^2u)] + [\exp(-r^2/4B^2u)][(u/4)(r^2/4B^2)(1 - u/9) + u - u^2/2.2! + u^3/3.3!] \quad \ldots (13)$$

Solution for short times--A solution that is more convenient for computations when t is small can be developed as follows. Making use of the integral relation [WATSON, 1944, p. 183]

$$2K_0(r/B) = \int_0^{\infty} (1/y)\,\exp[-y - r^2/4B^2y]\,dy$$

combining (8) with (6) and making the substitutions, $r^2/4B^2y = Z$, (6) reduces to

$$s/(Q/4\pi T) = \int_u^{\infty} (1/Z)\,\exp[-Z - r^2/4B^2Z]\,dZ \quad \ldots\ldots (14)$$

where

$$u = r^2S/4Tt$$

It is of interest to note that if $B \rightarrow \infty$, that is, either when leakage is very small or when the time is very small so that leakage does not have time to enter the main flow, (14) becomes

$$s/(Q/4\pi T) = \int_u^{\infty} (1/Z)\,\exp(-Z)\,dZ \quad \ldots\ldots (15)$$

which is the solution to the problem if leakage is not present [THEIS, 1935].

The integral of (14), being similar to that of (8), can be evaluated in the same way. The final expression is

$$s/(Q/4\pi T) = I_0(r/B)\,[-Ei(-u)] - e^{-u}\Big\{0.5772 + \ln(r^2/4B^2u) + [-Ei(-r^2/4B^2u)] - (r^2/4B^2u) + [I_0(r/B) - 1]/u\Big\} + (e^{-u}/u^2)\sum_{n=1}^{\infty}\sum_{m=1}^{n} \frac{(-1)^{n+m}\,(n-m+1)!\,(r^2/4B^2)^n}{(n+2)!^2\,u^{n-m}} \quad \ldots\ldots (16)$$

which is in a form convenient for computation with values of $u \geq 1$. Very few terms of the series need be used when $r/2B \leq 1$ and $u \geq 1$. For values of $u \geq 5$ and values of $r/2B \leq 1$, the series may be safely neglected and results obtained accurate to four decimal places. If $r/2B \leq 0.10$ and $u \geq 1$, the solutions can be approximated by

$$s/(Q/4\pi T) = I_0(r/B)\,[-\,\mathrm{Ei}(-u)] - e^{-u}\,[(r^2/4B^2)(1/u - 1/36u^2) + (r^2/4B^2)^2\,(1/4u - 1/4u^2)] \quad \ldots\ldots (17)$$

Drawdown at the well--The drawdown at the face of the well is found by substituting r_w for r in any of the previous solutions, r_w being the radius of the well. However, if the ratio $r_w/B \leq 0.01$ the drawdown at the face of the well will, for all practical purposes, be given by

$$s_w/(Q/4\pi T) = -\,\mathrm{Ei}(-u_w) \quad \ldots\ldots (18)$$

which is the drawdown at the well if there is no leakage. Eq. (18) is obtained by making r/B very small in either (12) or (17).

Calculated example--Tables 1 and 2 were prepared to facilitate evaluation of (11) and (16). It gives a few coefficients of the double series that appears in both equations. The numbers in brackets in the body of the table are negative powers of ten by which the other numbers are multiplied.

Table 1--Values of $(n - m + 1)!/(n + 2)!^2$ found in Equations (11) and (16)

n	m							
	1	2	3	4	5	6	7	8
1	2.7778[-2]	......	......	......	......	......	......	......
2	3.4722[-3]	1.7361 [-3]	......	......	......	......	......	......
3	4.1667[-4]	1.3889 [-4]	6.9444 [-5]	......	......	......	......	......
4	4.6296[-5]	1.1574 [-5]	3.8580 [-6]	1.9290 [-6]	......	......	......	......
5	4.7240[-6]	9.4481 [-7]	2.3620 [-7]	7.8734 [-8]	3.9367 [-8]	......	......	......
6	4.4287[-7]	7.3814 [-8]	1.4763 [-8]	3.6907 [-9]	1.2302 [-9]	6.1512[-10]	......	......
7	3.8274[-8]	5.4677 [-9]	9.1129[-10]	1.8226[-10]	4.5564[-11]	1.5188[-11]	7.5940[-12]	......
8	3.0619[-9]	3.8274[-10]	5.4677[-11]	9.1129[-12]	1.8226[-12]	4.5564[-13]	1.5188[-13]	7.5940[-14]

Table 2--Values of $(r^2/4B^2)^m$ for B = 20,000 ft

r	r/2B	m			
		1	2	3	4
ft					
1,000	0.025	6.25 [-4]	3.9062[-7]	....	....
2,000	0.05	2.5 [-3]	6.25 [-6]	1.5625[-8]	....
5,000	0.125	1.5625[-2]	2.4414[-4]	3.7903[-6]	5.9223[-8]
10,000	0.25	6.25 [-2]	3.9062[-3]	2.4414[-4]	1.5259[-5]
20,000	0.50	2.5 [-1]	6.25 [-2]	1.5625[-2]	3.9062[-3]
50,000	1.25	1.5625	2.4414	3.7903	5.9223

Drawdown values for one set of assumed values of the parameters are given in Table 3 and are represented graphically in Figure 1. The factor B is taken to be 20,000 ft. The abscissa is $4Tt/S = r^2/u$ and represents the time multiplied by a constant. The straight line marked 'zero leakage' shows the trend that the drawdown would take at a distance of 1000 ft if the leakage were zero ($B \rightarrow \infty$). The effect of leakage is shown by the departure of the drawdown curve from this straight line as time increases. The effect of leakage is shown also by the drawdown curves for the more remote distances.

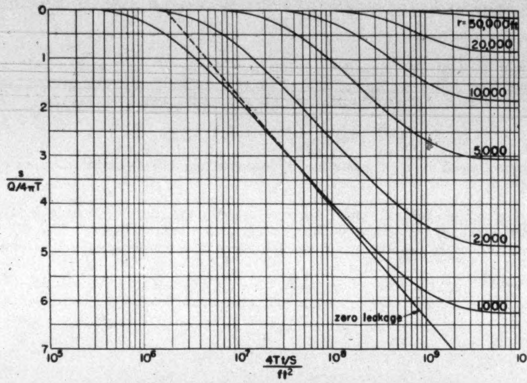

Fig. 1--Variation of drawdown with time at different distances in an infinite leaky aquifer with B = 20,000 ft

Table 3--Values of $s/(Q/4\pi T)$ for B = 20,000 ft

u	r (in feet)					
	1000	2000	5000	10,000	20,000	50,000
0.0002	6.217	....	....	....	....	....
0.0005	6.082	....	....	....	....	....
0.001	5.796	4.829	....	....	....	....
0.002	5.354	4.708	....	....	....	....
0.005	4.608	4.296	3.072	....	....	....
0.01	3.979	3.815	2.993	....	....	....
0.02	3.326	3.244	2.766	1.838	....	....
0.05	2.457	2.427	2.230	1.708	....	....
0.10	1.818	1.805	1.715	1.443	0.819	....
0.20	1.221	1.215	1.187	1.060	0.715	....
0.50	0.559	0.558	0.550	0.521	0.420	0.117
1.0	0.219	0.218	0.218	0.210	0.185	0.080

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NON-STEADY GREEN'S FUNCTIONS FOR AN INFINITE STRIP OF LEAKY AQUIFER

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Abstract--Solutions are obtained for the non-steady flow to a well in an infinite-strip of leaky aquifer whose boundaries are maintained either at a constant head or at a vanishing flux. These solutions are used to deduce the corresponding solutions for non-leaky aquifers. Also they are used to obtain the non-steady Green's functions for the infinite-strips. Green's functions are tabulated for infinite quadrants and half-planes.

Introduction--The partial differential equation for non-steady flow in leaky aquifers has been integrated for special cases [JACOB, 1946; HANTUSH, 1949; HANTUSH and JACOB, 1954]. The equation in polar coordinates is

$$(\partial^2 s/\partial r^2) + (1/r)(\partial s/\partial r) - (s/B^2) = (S/T)(\partial s/\partial t) \quad \ldots\ldots\ldots\ldots\ldots (1)$$

where s = the drawdown at a point a distance $r = \sqrt{(x - x_1)^2 + (y - y_1)^2}$ from the center of the well (x_1, y_1) and at time t from the start; S = storage coefficient (volume of water which a unit decline of head releases from storage in a vertical prism of the aquifer of unit cross section); T = transmissibility of the aquifer (discharge per unit normal width per unit hydraulic decline); B = leakage factor, which is equal to $(Tb'/K')^{1/2}$ [HANTUSH and JACOB, 1954], b' and K' are respectively the thickness and the transmission constant or 'permeability' of the semi-impervious confining bed, through which vertical leakage takes place in proportion to the drawdown.

In the present paper it is shown how the solution obtained in the paper on Non-steady radial flow in an infinite leaky aquifer [HANTUSH and JACOB, 1955] can be utilized to obtain a solution for the non-steady flow in an infinite-strip of a leaky aquifer, if the boundaries of the strip are kept either at a constant head or at a vanishing flux.

The systems correspond to a well located between two parallel rivers or canals, or, in the case where there is no flux across the boundaries, to a well between parallel impermeable boundaries, such as two parallel faults or buried bedrock walls or ledges. The solutions are of practical interest, especially in artificial drainage of land and in relieving pressures underneath river levees.

Analysis--In this problem of a leaky aquifer, a body of ponded water or a bed of sand in which there is a water table overlies a semi-pervious bed of thickness b' and permeability K'. The latter confines an artesian sand of thickness b and permeability K, which rests on an impervious layer. A well is screened in the artesian sand.

The drawdown produced by a well starting from rest and discharging at a steady rate from such an aquifer of uniform thickness and permeability and infinite extent [HANTUSH and JACOB, 1955] is given by

$$s/(Q/4\pi T) = \int_u^\infty \exp[-x - (r^2/4B^2)/x]\,(dx/x) \quad \ldots\ldots\ldots\ldots\ldots (2)$$

where Q = discharge of well, $u = (r^2 S/4Tt)$, the remaining symbols being as defined above.

Making the substitution $x = r^2 Z$, (2) becomes

$$s/(Q/4\pi T) = \int_{(S/4Tt)}^\infty \left\{\exp[-r^2 Z - (1/4B^2 Z)]\right\}(dZ/Z) \quad \ldots\ldots\ldots\ldots (3)$$

Due to the linearity and homogeneity of (1), the method of images can be used to obtain zero drawdown or vanishing flux or a combination of both on the boundaries of different geometrical forms.

The appropriate image system which results in zero drawdown along the boundaries of the infinite-strip, 2a wide, is shown in Figure 1.

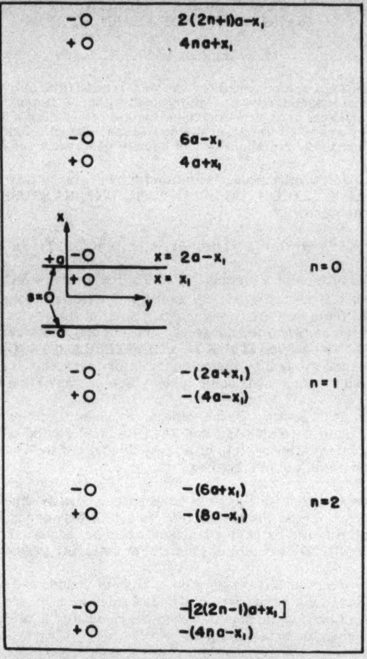
-O
2(2n+1)a-x₁
+O
4na+x₁
-O
6a-x₁
+O
4a+x₁
x
+a
-O
x= 2a-x₁
+O
x= x₁
n=0
s=O
y
-a
-O
-(2a+x₁)
n=1
+O
-(4a-x₁)
-O
-(6a+x₁)
n=2
+O
-(8a-x₁)
-O
-[2(2n-1)a+x₁]
+O
-(4na-x₁)

Fig. 1--Image system which gives zero drawdown along $x = \pm a$; the actual well is at (x_1, y_1); the images extend to $\pm\infty$; discharging wells and recharging wells are indicated by (+) and (-) signs respectively

The drawdown distribution in the infinite-strip is the resultant of the drawdown produced by all the images of this system and may, therefore, be written as

$$s/(Q/4\pi T) = \sum_{n=-\infty}^{\infty} \int_{(S/4Tt)}^{\infty} \Big(\exp\left\{- Z\left[(x - x_1 - 4na)^2 + (y - y_1)^2\right]\right\} - \exp\left\{- Z\left[(x + x_1 - 2a - 4na)^2 + (y - y_1)^2\right]\right\}\Big) \left[\exp(-1/4B^2Z)\right](dZ/Z) \quad \ldots . (4)$$

Interchanging summation and integration [BROMWICH, 1947] and simplifying, (4) becomes

$$s/(Q/4\pi T) = \int_{(S/4Tt)}^{\infty} \left\{\exp\left[-(y-y_1)^2 Z - 1/4\, B^2 Z\right]\right\} (\Sigma)\,(dZ/Z) \quad \ldots\ldots\ldots \quad (5)$$

where

$$\Sigma = \sum_{n=-\infty}^{\infty} \left(\exp\left\{-16a^2 Z\left[(x-x_1)(1/4a) - n\right]^2\right\} - \exp\left\{-16a^2 Z\left[(x+x_1-2a)(1/4a) - n\right]^2\right\}\right) \quad \ldots\ldots\ldots \quad (6)$$

Eq. (6) can be reduced as follows. First, by the aid of the integral relation [INGERSOLL and ZOBEL, 1948]

$$\sqrt{2/\pi} \int_0^{\infty} \left[\exp(-p^2t^2)\right] \cos(\alpha t)\, dt = (1/\sqrt{2p^2}) \exp(-\alpha^2/4p^2)$$

the following relation can readily be obtained

$$\sqrt{2/\pi} \int_0^{\infty} \left\{\left[\exp(-p^2t^2)\right] \cos(bt)\right\} \cos(\alpha t)\, dt = (1/2\sqrt{2p^2}) \left\{\exp\left[-(\alpha+b)^2/4p^2\right] + \exp\left[-(\alpha-b)^2/4p^2\right]\right\} \quad \ldots\ldots\ldots \quad (7)$$

Also, from (7), the Fourier cosine transform for the function

$$f(t) = \left[\exp(-p^2t^2)\right] \cos(bt) \quad \ldots\ldots\ldots \quad (8)$$

is given by

$$F_c(\alpha) = (1/2\sqrt{2p^2}) \left\{\exp\left[-(\alpha+b)^2/4p^2\right] + \exp\left[-(\alpha-b)^2/4p^2\right]\right\} \quad \ldots\ldots\ldots \quad (9)$$

Poisson's formula [TITCHMASCH, 1937] gives the following relation

$$\sqrt{\beta}\left[(1/2)\, F_c(0) + \sum_{n=1}^{\infty} F_c(n\beta)\right] = \sqrt{\theta}\left[(1/2)\, f(0) + \sum_{n=1}^{\infty} f(n\theta)\right] \quad \ldots\ldots\ldots \quad (10)$$

where $f(t)$ = a function that tends to zero as $t \to \infty$; $F_c(\alpha)$ = the Fourier cosine transform of $f(t)$; and $\theta\beta = 2\pi$ with $\theta > 0$.

Taking $\beta = 1$ and $\theta = 2\pi$ and substituting in (10) the equivalent expressions of $f(t)$ and $F_c(\alpha)$ from the relations (8) and (9), one obtains

$$(1/2\sqrt{2p^2}) \left(\exp(-b^2/4p^2) + \sum_{n=1}^{\infty} \left\{\exp\left[-(n+b)^2/4p^2\right] + \exp\left[-(n-b)^2/4p^2\right]\right\}\right)$$

$$= \sqrt{2\pi} \left(1/2 + \sum_{n=1}^{\infty} \left\{\exp\left[-(2n\pi p)^2\right]\right\} \cos(2n\pi b)\right) \quad \ldots\ldots\ldots \quad (11)$$

Letting n in the first sum of the left-hand member of (11) take negative values, and combining the result, one obtains

$$\sum_{n=-\infty}^{\infty} \exp\left[-(b-n)^2/4p^2\right] = 2\sqrt{4\pi p^2} \left(1/2 + \sum_{n=1}^{\infty} \left\{\exp\left[-(2n\pi p)^2\right]\right\} \cos(2n\pi b)\right) \quad \ldots \quad (12)$$

Taking $b = (x - x_1)/4a$ and $(1/4p^2) = 16a^2Z$, (12) reduces to

$$\sum_{n=-\infty}^{\infty} \exp\left\{-16a^2Z\left[(x - x_1)(1/4a) - n\right]^2\right\} = (1/2a)\sqrt{\pi/Z}\,\Bigg(1/2$$

$$+ \sum_{n=1}^{\infty}\left\{\exp\left[-(n\pi/2a)^2/4Z\right]\right\}\cos\left[n\pi(x - x_1)/2a\right]\Bigg) \quad \ldots\ldots\ldots\ldots\ldots (13)$$

Again, taking $b = (x + x_1 - 2a)(1/4a)$ and $(1/4p^2) = 16a^2Z$, (12) gives

$$\sum_{n=-\infty}^{\infty} \exp\left\{-16a^2Z\left[(x + x_1 - 2a)(1/4a) - n\right]^2\right\} = (1/2a)\sqrt{\pi/Z}\,\Bigg(1/2$$

$$+ \sum_{n=1}^{\infty}\left\{\exp\left[-(n\pi/2a)^2/4Z\right]\right\}\cos\left[n\pi(x + x_1 - 2a)/2a\right]\Bigg) \quad \ldots\ldots\ldots\ldots\ldots (14)$$

Substracting (14) from (13) and simplifying, one finds

$$\Sigma = (1/a)\sqrt{\pi/Z}\sum_{n=1}^{\infty} R_n \exp\left[-(n\pi/2a)^2/4Z\right] \quad \ldots\ldots\ldots\ldots\ldots (15)$$

where Σ is the sum in (6) above, and where

$$R_n = \sin\left[n\pi(x - a)/2a\right]\sin\left[n\pi(x_1 - a)/2a\right] \quad \ldots\ldots\ldots\ldots\ldots (16)$$

On replacing Σ in (5) by its equivalent from (15) and reversing the order of summation and integration, (5) can be expressed as

$$s/(Q/4\pi T) = \sum_{n=1}^{\infty} R_n \int_{(S/4Tt)}^{\infty} (\sqrt{\pi}/a)\left(\exp\left\{-(y - y_1)^2Z - \left[1/B^2 + (n\pi/2a)^2\right]/4Z\right\}\right)(dZ/Z^{3/2})$$

$$\ldots\ldots\ldots\ldots\ldots (17)$$

The infinite integral in (17), designated by I, is evaluated as follows

$$I = (\sqrt{\pi}/a)\int_{(S/4Tt)}^{\infty}\left(\exp\left\{-(y - y_1)^2Z - (\pi/2a)^2\left[n^2 + (2a/\pi B)^2\right]/4Z\right\}\right)(dZ/Z^{3/2})$$

$$= (8/\sqrt{\pi})\left[1/\sqrt{n^2 + (2a/\pi B)^2}\right]\int_0^{\lambda_1}\exp\left\{-\lambda^2 - (\pi/4a)^2\left[n^2 + (2a/\pi B)^2\right](y - y_1)^2(1/\lambda^2)\right\}d\lambda$$

$$\ldots\ldots\ldots\ldots\ldots (18)$$

where the following substitution has been made

$$\lambda = \left[\pi\sqrt{n^2 + (2a/\pi B)^2}\right]/(4a\sqrt{Z})$$

also, λ_1 stands for $\left[\pi\sqrt{n^2 + (2a/\pi B)^2}\right]/(4\sqrt{a^2S/4Tt})$.

Eq. (18) can be changed to a more useful form with the aid of the integration formula [BINET, 1841]

$$(2/\sqrt{\pi})\int_0^{\alpha_1}\exp\left[-\alpha^2 - (\beta/\alpha)^2\right]d\alpha = (1/2)\left[\exp(-2\beta)\right]$$

$$\times\,\mathrm{erfc}\left[(\beta/\alpha_1) - \alpha_1\right] - (1/2)\left[\exp(2\beta)\right]\mathrm{erfc}\left[(\beta/\alpha_1) + \alpha_1\right]$$

where the complementary error function is

$$\operatorname{erfc}(x) = 1 - \operatorname{erf}(x) = (2/\sqrt{\pi}\,) \int_x^{\infty} e^{-\gamma^2} d\gamma$$

Eq. (18) may, therefore, take the form

$$\begin{aligned} I = (2/\delta) \Big(&\Big\{\exp\left[-(\pi\delta/2a)|y - y_1|\right]\Big\} \operatorname{erfc}\Big\{\sqrt{(y - y_1)^2 S/4Tt} - \left[(\pi\delta/4)/\sqrt{a^2 S/4Tt}\right]\Big\} \\ &- \Big\{\exp\left[(\pi\delta/2a)|y - y_1|\right]\Big\} \operatorname{erfc}\Big\{\sqrt{(y - y_1)^2 S/4Tt} + \left[(\pi\delta/4)/\sqrt{a^2 S/4Tt}\right]\Big\}\Big) \quad \ldots\ldots\ldots (19) \end{aligned}$$

where $\delta = \sqrt{n^2 + (2a/\pi B)^2}$.

Drawdown distribution for zero drawdown on the boundaries in a leaky aquifer--Finally, on inserting (19) in (17), the drawdown distribution will be

$$\begin{aligned} s/(Q/2\pi T) = \sum_{n=1}^{\infty} (R_n/\delta) \Big(&\Big\{\exp\left[-(\pi\delta/2a)|y - y_1|\right]\Big\} \operatorname{erfc}\Big\{\sqrt{u_y} - \left[(\pi\delta/4)/\sqrt{u_a}\right]\Big\} \\ &- \Big\{\exp\left[(\pi\delta/2a)|y - y_1|\right]\Big\} \operatorname{erfc}\Big\{\sqrt{u_y} + \left[(\pi\delta/4)/\sqrt{u_a}\right]\Big\}\Big) \quad \ldots\ldots\ldots\ldots (20) \end{aligned}$$

where $R_n = \sin[n\pi(x - a)/2a] \sin[n\pi(x_1 - a)/2a]$; $u_y = (y - y_1)^2 S/4Tt$; and $u_a = a^2 S/4Tt$.

Since the values of the terms of the series of (20) can be found from tables and since the series tends to zero quite rapidly as n increases, it can be seen that the equation is not an inconvenient one for the computation of the drawdown.

Recalling that $\operatorname{erfc}(-\infty) = 2$ and $\operatorname{erfc}(\infty) = 0$, as time becomes great, that is, as $t \to \infty$, (20) is seen to take the form

$$s/(Q/2\pi T) = 2 \sum_{n=1}^{\infty} (R_n/\delta) \exp\left[-(\pi\delta/2a)|y - y_1|\right] \quad \ldots\ldots\ldots\ldots (21)$$

which as should be expected is the steady state solution of the problem [HANTUSH, 1949].

Drawdown at the well face--At the face of the well, $(y - y_1) = 0$, $(x - x_1) = r_w$, and $(x + x_1) = 2x$, where (x_1, y_1) are the coordinates of the well center, and r_w is its radius. For the above values (20) gives, after simplification

$$s_w/(Q/2\pi T) = \sum_{n=1}^{\infty} (1/\delta)\left[\cos(n\pi r_w/2a) - (-1)^n \cos(n\pi x_1/a)\right] \Big\{1 - \operatorname{erfc}\left[(\pi\delta/4)/\sqrt{u_a}\right]\Big\} \quad \ldots\ldots\ldots\ldots\ldots\ldots (22)$$

where s_w = drawdown at the well face.

The first infinite sum of (22) gives the steady-state drawdown at the well face, which has been tabulated and illustrated graphically [HANTUSH, 1949] for several practical values of the parameters involved, while the second infinite sum may be considered as a superposed transient state. It can be seen that, for all practical values of r_w/a, $[(r_w/a) < 0.001]$ and of u_a, $[u_a > 0.02]$, the transient solution may be considered as independent of the well size, that is, of (r_w/a) if $(r_w/a) < 0.001$.

Figure 2 is prepared to illustrate the variation with time of the drawdown at the face of the well for different values of leakage; the data on which it is based are given in Table 1. The curves shown are constructed for $(r_w/a) = 0.0001$ with the well at the center of the strip.

Figure 4 gives the steady drawdown curves, expressed in terms of the ratio $s_w/(Q/2\pi T)$, for various values of (x_1/a), (a/B), and (a/r_w) while Figure 3 gives the transient drawdown, in terms of $s'_w/(Q/2\pi T)$ at the well face with the well at the center of the strip and with $(a/r_w) \geq 1000$. The two figures may be used to find the drawdown at the face of a well centered at (0, 0) for values of $(a/r_w) \geq 1000$. Table 2 gives values on which Figure 3 is based.

Table 1--Values of $s_w/(Q/2\pi T)$ in an infinite strip of a leaky aquifer with well at (0, 0) discharging at rate Q; drawdown is zero at $x = \pm a$; $(a/r_w) = 10,000$

$1/u_a$	a/B		
	0	$\pi/2$	π
0.01	6.619	6.610	6.608
0.02	6.962	6.960	6.944
0.05	7.430	7.409	7.366
0.10	7.770	7.740	7.658
0.20	8.119	8.058	7.886
0.50	8.586	8.433	8.108
1.	8.917	8.653	8.169
2.	9.219	8.781	8.181
5.	9.446	8.817	8.181
10.	9.452	8.818	8.181

Table 2--Values of $s'_w/(Q/2\pi T)$ transient drawdown at well face, with well at center of strip; drawdown is zero at $x = \pm a$; $(a/r_w) \geq 1000$

$1/u_a$	a/B		
	0	$\pi/2$	π
0.01	2.833	2.208	1.573
0.02	2.490	1.858	1.237
0.05	2.022	1.409	0.815
0.10	1.682	1.078	0.523
0.20	1.333	0.760	0.295
0.50	0.866	0.385	0.073
1.	0.535	0.165	0.012
2.	0.233	0.037	0.004
5.	0.0056	0.001	....
10.	....	....	....

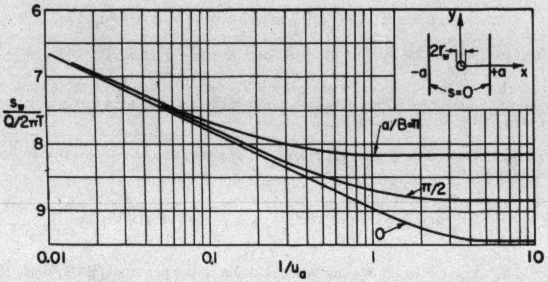

Fig. 2--Time-drawdown curves at well face in an infinite strip of a leaky aquifer with well at (0,0) and discharging at rate Q; drawdown is zero at $x = \pm a$; $(a/r_w) = 10,000$

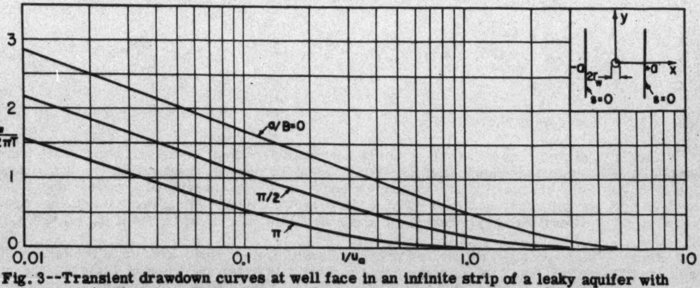

Fig. 3--Transient drawdown curves at well face in an infinite strip of a leaky aquifer with well at (0, 0) and discharging at rate Q; drawdown is zero at $x = \pm a$; $(a/r_w) \geq 1000$

Drawdown distribution for zero drawdown on the boundaries of a non-leaky aquifer--For a non-leaky aquifer, $B \rightarrow \infty$ or $(1/B) = 0$. Writing zero for $(1/B)$ in (20), the solution becomes

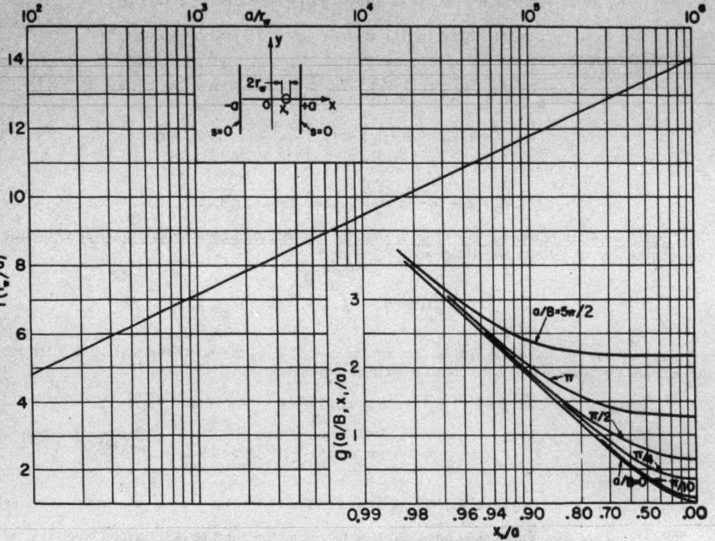

Fig. 4--Steady-state drawdown curves at well face in an infinite strip of a leaky aquifer with well at $(x_1, 0)$ and discharging at rate Q

$$s/(Q/2\pi T) = \sum_{n=1}^{\infty} (R_n/n) \left(\left\{ \exp\left[-(n\pi/2a)\left|y - y_1\right|\right] \right\} \times \operatorname{erfc}\left(\sqrt{u_y} - n\pi/4\sqrt{u_a}\right) - \left\{ \exp\left[(n\pi/2a)\left|y - y_1\right|\right] \right\} \operatorname{erfc}\left(\sqrt{u_y} + n\pi/4\sqrt{u_a}\right) \right) \quad \ldots\ldots (23)$$

The corresponding drawdown at the face of the well is

$$s_w/(Q/2\pi T) = \sum_{n=1}^{\infty} (1/n) \left[\cos(n\pi r_w/2a) - (-1)^n \cos(n\pi x_1/a)\right] \times \left[1 - \operatorname{erfc}\left(n\pi/4\sqrt{u_a}\right)\right] = (1/2) \ln \frac{1 + \cos(\pi x_1/a)}{1 - \cos(\pi r_w/2a)} - \sum_{n=1}^{\infty} (1/n)\left[\cos(n\pi r_w/2a) - (-1)^n \cos(n\pi x_1/a)\right] \operatorname{erfc}\left(n\pi/4\sqrt{u_a}\right) \quad \ldots\ldots (24)$$

Drawdown distribution for zero flux across the boundaries in a leaky aquifer--The images that result in a vanishing flux across the boundaries are located at the same positions with respect to the boundaries as those in Figure 1; they differ only, but importantly, in the question of sign. All the images have positive signs, that is, they are taken as sinks. The solution is then obtained by adding, instead of subtracting, the two infinite sums of (4). Consequently, in the process of derivation, (13) and (14) are added. The other steps are carried out in the same manner. The solution is finally reduced to

$$
\begin{aligned}
s/(Q/2\pi T) = (\pi B/4a) \Big(&\left\{\exp\left[-(1/B)\,|y - y_1|\right]\right\} \operatorname{erfc}\left(\sqrt{u_y} - a/2B\sqrt{u_a}\right) \\
&- \left\{\exp\left[(1/B)\,|y - y_1|\right]\right\} \operatorname{erfc}\left(\sqrt{u_y} + a/2B\sqrt{u_a}\right)\Big) \\
&+ \sum_{n=1}^{\infty} (F_n/\delta) \Big(\left\{\exp\left[-(\pi\delta/2a)\,|y - y_1|\right]\right\} \operatorname{erfc}\left\{\sqrt{u_y} - \left[(\pi\delta/4)/\sqrt{u_a}\right]\right\} \\
&- \left\{\exp\left[(\pi\delta/2a)\,|y - y_1|\right]\right\} \operatorname{erfc}\left\{\sqrt{u_y} + \left[(\pi\delta/4)/\sqrt{u_a}\right]\right\}\Big) \quad \ldots\ldots\ldots\ldots (25)
\end{aligned}
$$

where

$$F_n = \cos\left[n\pi(x - a)/2a\right] \cos\left[n\pi(x_1 - a)/2a\right] \quad \ldots\ldots\ldots\ldots (26)$$

Drawdown distribution for zero flux across the boundaries in a non-leaky aquifer--Starting with the equation for an infinite non-leaky aquifer, namely

$$s/(Q/4\pi T) = \int_u^{\infty} e^{-x}\,(dx/x)$$

and carrying out the steps followed in the development of (25), the drawdown distribution for zero flux across the boundaries of the infinite strip of a non-leaky aquifer is found to be

$$
\begin{aligned}
s/(Q/2\pi T) = (\sqrt{\pi}/2a)\,|y - y_1| &\left\{\left[\exp(-u_y)\right](1/\sqrt{u_y}) - \sqrt{\pi}\ \operatorname{erfc}(\sqrt{u_y})\right\} \\
&+ \sum_{n=1}^{\infty} (F_n/n) \Big(\left\{\exp\left[-(n\pi/2a)\,|y - y_1|\right]\right\} \operatorname{erfc}\left(\sqrt{u_y} - n\pi/4\sqrt{u_a}\right) \\
&- \left\{\exp\left[(n\pi/2a)\,|y - y_1|\right]\right\} \operatorname{erfc}\left(\sqrt{u_y} + n\pi/4\sqrt{u_a}\right)\Big) \quad \ldots\ldots\ldots\ldots (27)
\end{aligned}
$$

The above equation could have been obtained by taking the limit of (25) (using l'Hopital's rule of limits) as $(1/B) \to 0$.

It is to be mentioned here that by proper combination of the solutions of the infinite strip, the drawdown distribution can be obtained for the infinite half-strips and for the rectangles along whose boundaries, the flux, the drawdown, or both vanish.

Non-steady Green's function for leaky aquifers--A clear definition of the non-steady Green's function can be given after the following principles are established [SOMMERFELD, 1949, p. 44].

(a) The equation of non-steady plane flow in leaky aquifers is given by (1) and may be written as

$$L(s) = (\partial^2 s/\partial x^2) + (\partial^2 s/\partial y^2) - (S/T)(\partial s/\partial t) - (s/B^2) = 0 \quad \ldots\ldots\ldots\ldots (28)$$

where L(s) is the differential expression of the equation.

(b) The adjoint equation to (28); if $v(x, y, t)$ is an integrating factor for the equation $L(s) = 0$, then v must satisfy

$$M(v) = (\partial^2 v/\partial x^2) + (\partial^2 v/\partial y^2) + (S/T)(\partial v/\partial t) - (v/B^2) = 0 \quad \ldots\ldots\ldots\ldots (29)$$

which is called the adjoint equation of $L(s) = 0$.

(c) The adjoint differential expression; if s and v are any two arbitrary functions of (x,y,t), then the adjoint $M(v)$ of $L(s)$ is defined by the property that

$$vL(s) - sM(v) = (\partial A/\partial x) + (\partial B/\partial y) + (\partial C/\partial t) \quad \ldots\ldots\ldots\ldots (30)$$

where A, B, and C are functions of s, v, and of their derivatives, which make the expression on the left-hand side of the equation integrable.

It can be shown that the above requirement is met if, by virtue of (29), one obtains the expression $M(v)$. Then, by substituting $L(s)$ and $M(v)$ in (30) and equating like terms, one will find that

$$\left.\begin{aligned} A &= v(\partial s/\partial x) - s(\partial v/\partial x) \\ B &= v(\partial s/\partial y) - s(\partial v/\partial y) \\ C &= -(S/T)\,sv \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (31)$$

(d) The delta-function; a function of as many independent variables as may be required, say $s(x, y, z; x_1, y_1, z_1)$ is called a delta function if it vanishes when $Z \rightarrow Z_1$ for all values of $(x, y) \neq (x_1, y_1)$ and it becomes infinite at $(x, y) = (x_1, y_1)$ so that

$$\int_{x_1-\epsilon}^{x_1+\epsilon} \int_{y_1-\epsilon}^{y_1+\epsilon} \delta \, dy \, dx = 1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (32)$$

With these principles in mind, we may now define the non-steady Green's function for leaky aquifers. A function $g(x, y, t; x_1, y_1, \tau)$ is called the non-steady Green's function for leaky aquifers if it has the following properties.

(a) Is a solution of the adjoint equation of the equation of the non-steady plane flow in leaky aquifers, namely: $M(g) = 0$.

(b) Is a delta-function.

(c) Is symmetrical in the two points (x, y) and (x_1, y_1) at any fixed time.

(d) Either (i) vanishes on the boundary of (ii), its normal derivative, vanishes on the boundary.

If such a function can be found for a given region, and if the initial drawdown is given and the drawdown or the flux are known on the boundary of the region, then the drawdown distribution in the interior of the region will be given by

$$\begin{aligned} s(P, \tau) = & \iint g_o(P, \tau; Q, 0) \, s_o(Q, 0) \, dA \\ & + (T/S) \int_o^{\tau} \oint_S \Big\{ [g_b(P, \tau; Q_b, t)] \, [\partial s(Q, t)/\partial n]_b \\ & - s_b(Q_b, t) \, [\partial g(P, \tau; Q, t)/\partial n]_b \Big\} \, dS \, dt \quad \ldots\ldots\ldots\ldots\ldots\ldots (33) \end{aligned}$$

where $s(P, \tau)$ is the drawdown at any point (P) in the region and at any time τ from the start, g_o and s_o are the initial Green's function and the initial drawdown respectively; the subscript b indicates evaluation of the functions on the boundary of the region; and n is the outward normal to the elemental length dS. The first integral is taken over all the region, and the second integral is taken over the lateral surface of the three-dimensional space-time prism (or cylinder).

To develop (33), one proceeds as follows: Let Figure 5 represent a space-time prism for which the Green's function is known. Let the point at which the drawdown is sought be (P, τ) and let the general moving point be (Q, t). The Gauss Theorem (or Green's lemma) in space for the coordinate system of Figure 5 is

$$\iiint [(\partial A/\partial x) + (\partial B/\partial y) + (\partial C/\partial t)] \, dV = \iint [A \cos(n, x) + B \cos(n, y) + C \cos(n, t)] \, d\sigma \quad \ldots (34)$$

where A, B, C are functions of (x, y, t), dV and $d\sigma$ are respectively the elemental volume and the elemental surface of the space considered; and (n, x), (n, y), and (n, t) are the angles between the outward normal to the surface and the cooresponding axis.

If the volume integrals of the two sides of (30) are taken, one obtains

$$\iiint [vL(s) - sM(v)] \, dV = \iiint [(\partial A/\partial x) + (\partial B/\partial y) + (\partial C/\partial t)] \, dV$$

Letting v = g the Green's function of the space considered, and applying Gauss Theorem, the above equation reduces to

$$\iiint [gL(s) - sM(g)] \, dV = \iint [A \cos(n, x) + B \cos(n, y) + C \cos(n, t)] \, d\sigma$$

The left-hand side of the above equation vanishes because (s) and (g) are respectively solutions of $L(s) = 0$ and $M(g) = 0$; hence the equation becomes

$$\iint [A \cos(n, x) + B \cos(n, y) + C \cos(n, t)] \, d\sigma = 0$$

Table 3--Green's functions for leaky and for non-leaky systems

Shape of region	Green's functions		
	Boundary values	Leaky systems	Non-leaky systems
Infinite plane	. . . .	$A \cdot (I)$	$B \cdot (I)$
Infinite half-plane with y-axis as the boundary	Vanishes on $x = 0$	$A \cdot (I - II)$	$B \cdot (I - II)$
	Normal derivative vanishes on $x = 0$	$A \cdot (I + II)$	$B \cdot (I + II)$
Infinite quadrant with the boundaries along the coordinate axes	Vanishes on the boundaries	$A \cdot (I - II - III + IV)$	$B \cdot (I - II - III + IV)$
	Vanishes on $x = 0$, and its normal derivative vanishes on $y = 0$	$A \cdot (I + II - III - IV)$	$B \cdot (I + II - III - IV)$
	Normal derivative vanishes on the boundaries	$A \cdot (I + II + III + IV)$	$B \cdot (I + II + III + IV)$
Infinite strip of width equals (2a) with the boundaries parallel to the y-axis	Vanishes on the boundaries	$C \sum_{n=1}^{\infty} R_n \exp(-u_y - D)$	$C \sum_{n=1}^{\infty} R_n \exp(-u_y - E)$
	Vanishes on $x = a$, and its normal derivative vanishes on $x = -a$	$C \sum_{n=1}^{\infty} O_n \exp(-u_y - P)$	$C \sum_{n=1}^{\infty} O_n \exp(-u_y - H)$
	Normal derivative vanishes on the boundaries	$(1/2)\, C \exp(-u_y - V)$ $- C \sum_{n=1}^{\infty} F_n \exp(-u_y - D)$	$(1/2)\, C \exp(-u_y)$ $- C \sum_{n=1}^{\infty} F_n \exp(-u_y - E)$

where

$I = \exp[-r_1^2 S/4T(\tau - t)]$

$II = \exp[-r_2^2 S/4T(\tau - t)]$

$III = \exp[-r_3^2 S/4T(\tau - t)]$

$IV = \exp[-r_4^2 S/4T(\tau - t)]$

$A = S/4\pi T(\tau - t) \exp[-T(\tau - t)/SB^2]$

$B = S/4\pi T(\tau - t)$

$C = \sqrt{\pi}\,[S/4\pi T(\tau - t)\, u_a]$

$D = \pi^2 [n^2 + (2a/\pi B)^2]/16u_a$

$E = (n\pi/4)^2/u_a$

$F_n = \cos(n\pi/2a)(x-a) \cos(n\pi/2a)(x_1-a)$

$H = [(2n - 1)\pi/4]^2/4u_a$

$O_n = (-1)^n \sin[(2n-1)\pi/4a](x-a) \cos[(2n-1)\pi/4a]x_1$

$P = \pi^2 [(2n - 1)^2 + (4a/\pi B)^2]/64u_a$

$R_n = \sin(n\pi/2a)(x-a) \sin(n\pi/2a)(x_1-a)$

$u_y = (y - y_1)^2 S/4T(\tau - t)$

$u_a = a^2 S/4T(\tau - t)$

$r_1 = \sqrt{(x_1 - x)^2 + (y_1 - y)^2}$

$r_2 = \sqrt{(x_1 + x)^2 + (y_1 - y)^2}$

$r_3 = \sqrt{(x_1 - x)^2 + (y_1 + y)^2}$

$r_4 = \sqrt{(x_1 + x)^2 + (y_1 + y)^2}$

$V = (a/B)^2/u_a$

Replacing A, B, and C by their values from (31), one obtains

$$\iint\left\{[g(\partial s/\partial x) - s(\partial g/\partial x)]\cos(n,x) + [g(\partial s/\partial y) - s(\partial g/\partial y)]\cos(n,y) - (S/T)\,g\,s\cos(n,t)\right\}d\sigma = 0 \qquad \ldots\ldots (35)$$

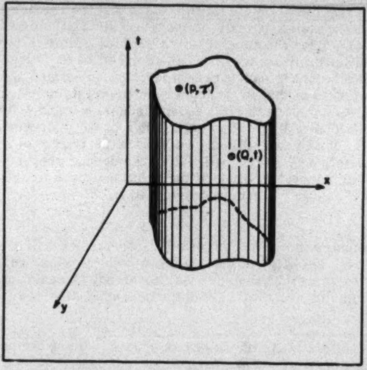

Fig. 5--Closed region for which the Green's function is known

Applying (35) to the surface of the right angled space time prism of Figure 5 excluding the point (P,τ) by a small 2ϵ square (with ϵ chosen arbitrarily small), the total surface integral will break down to the sum of the following surface integrals:

(a) The integral over the base of the prism of Figure 5; that is for $t = 0$. Over the base of the prism, $\cos(n,x) = \cos(n,y) = 0$, $\cos(n,t) = -1$, and $d\sigma = dx\,dy = dA$. Therefore, the surface integral of (35) becomes

$$(S/T)\iint g_o\ s_o\ dA$$

where g_o and s_o are the value of g and s for $t = 0$.

(b) The integral over the top of the prism where $t = \tau$. Over the top of the prism, $\cos(n,x) = \cos(n,y) = 0$, $\cos(n,t) = 1$, and $d\sigma = dx\,dy = dA$. Thus the integral of (35) becomes

$$-(S/T)\iint g_\tau\ s_\tau\ dA$$

where g_τ and s_τ are the values of g and s for $t = \tau$. But, since g is a delta function, the integral vanishes for all $(x, y) \neq (x_1, y_1)$ except at the point (P,τ) where by the property of the δ-function, it becomes $[-(S/T)\ s(P,\tau)]$. That is

$$-(S/T)\iint s_\tau g_\tau dA = -(S/T)\ s(P,\tau)\int_{x_1-\epsilon}^{x_1+\epsilon}\int_{y_1-\epsilon}^{y_1+\epsilon} g_\tau\,dx\,dy = -(S/T)\ s(P,\tau)$$

(c) The integral over the lateral surface of the prism of Figure 5 for $0 < t < \tau$. Over this surface $\cos(n,t) = 0$ and $d\sigma = dS\,dt$, where dS is the elemental length of the curve S (forming) the boundaries of the top and base of the prism. So the integral of (35) becomes

$$\int_o^\tau\oint_S\left\{[g_b(\partial s/\partial x)_b - s_b(\partial g/\partial x)_b]\cos(n,x) + [g_b(\partial s/\partial y)_b - s_b(\partial g/\partial y)_b]\cos(n,y)\right\}dS\,dt$$

which is equal

$$\int_o^\tau\oint_S [g_b(\partial s/\partial n)_b - s_b(\partial g/\partial n)_b]\,dS\,dt$$

where the subscript b indicate evaluation of the functions on the boundary, and where n is the outward normal to the curve.

Adding these integrals and rearranging terms, (33) will be obtained. This representation of $s(P,\tau)$ is general since the singular point (P,τ) can be situated at any arbitrary point $x = x_1$, $y = y_1$, and $t = \tau$.

Non-steady Green's functions for the infinite plane and for the infinite strip--The solutions obtained in the foregoing discussion, namely, those given by (2), (20), and (26), are solutions of the differential equation $L(s) = 0$ for the case in which the initial time is zero. They will be solutions for the case of a general initial time, $t = \tau$ if t is replaced by $(t - \tau)$. Furthermore, they fulfill the last two properties of the non-steady Green's function as defined above. To fulfill the first property of the Green's function, that is, to transform them into solutions of the adjoint equation $M(g) = 0$, one needs only to compare the two equations $L(s) = 0$ and $M(g) = 0$. This comparison will indicate that the solutions of $L(s) = 0$, with the sign of $(t - \tau)$ reversed, will be the corresponding solutions of $M(g) = 0$. It can easily be shown that the derivative of $s/(Q/4\pi T)$ in these solutions with respect to time multiplied by $S/4\pi T$ will fulfill the second property of the Green's function. Thus, the derivatives, with respect to time, of the solutions given by (2), (20), and (26) will be the non-steady Green's functions for the region considered if, after performing the differentiation, t is replaced by $(\tau - t)$.

It is of interest to mention here that the previous discussion will also apply to non-leaky systems if one looks upon L(s) and M(g) as the differential expressions representing the differential equations for non-leaky systems. Therefore, the non-steady Green's function for non-leaky systems can also be found (as outlined above) from the corresponding solutions of the non-leaky systems.

It is also to be noticed that while the solutions of $L(s) = 0$ are defined for the future of τ, that is, for $t > \tau$, the solutions of $M(g) = 0$ are defined for the past of τ, that is, for $t < \tau$.

Based upon the above analysis the non-steady Green's functions for several regions are given in Table 3.

Finally it may be mentioned that by proper combination of the Green's functions for the infinite strips, the Green's functions for the infinite half-strips and for the rectangles can be obtained.

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THE EFFECT ON STREAM FLOW OF THE KILLING OF SPRUCE AND PINE BY THE ENGELMANN SPRUCE BEETLE

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Abstract--An outbreak of the Engelmann spruce beetle on the White River Plateau of western Colorado killed the Engelmann spruce and lodgepole pine on a considerable portion of the 762-sq mi drainage basin of White River above the town of Meeker, Colorado. Statistical analyses were made to compare stream flow and water content of snow for White River with similar measurements made for the 206-sq mi drainage basin of Elk River above Clark, Colorado. The analyses show that the flow of White River increased after the beetle outbreak, and this increase is attributed to reduced interception of snow and to reduced transpiration by the beetle-killed trees. Total annual stream flow of White River was compared for three periods: (1) the 1937-1940 water years before the killing of the spruce and pine; (2) the 1941-1946 water years during which the beetle outbreak was most active; and (3) the 1947-1951 water years after the killing of the mature and overmature spruce and pine had been completed. The average annual stream flow increased by 1.22 inches during 1941-1946 and by 2.28 inches during 1947-1951 as compared to the period 1937-1940 after adjustment was made for climatic fluctuations.

Introduction--During recent years the Engelmann spruce beetle (*Dendroctonus engelmannii* (Hopk.)) has caused the death of Engelmann spruce (*Picea engelmannii* Parry) over large areas of the Rocky Mountains in western Colorado. On White River drainage a severe outbreak of this beetle began in 1941 and continued through 1946. At first, only the spruce on small areas was attacked, but by 1947 practically all Engelmann spruce and lodgepole pine (*Pinus contorta* Dougl.) larger than six inches in diameter were killed on a considerable portion of White River watershed. The Engelmann spruce beetle did not attack subalpine fir (*Abies lasiocarpa* (Hook) Nutt.), an associated tree species in the spruce stands, nor did it cause the death of smaller spruce and pine [WYGANT and NELSON, 1949].

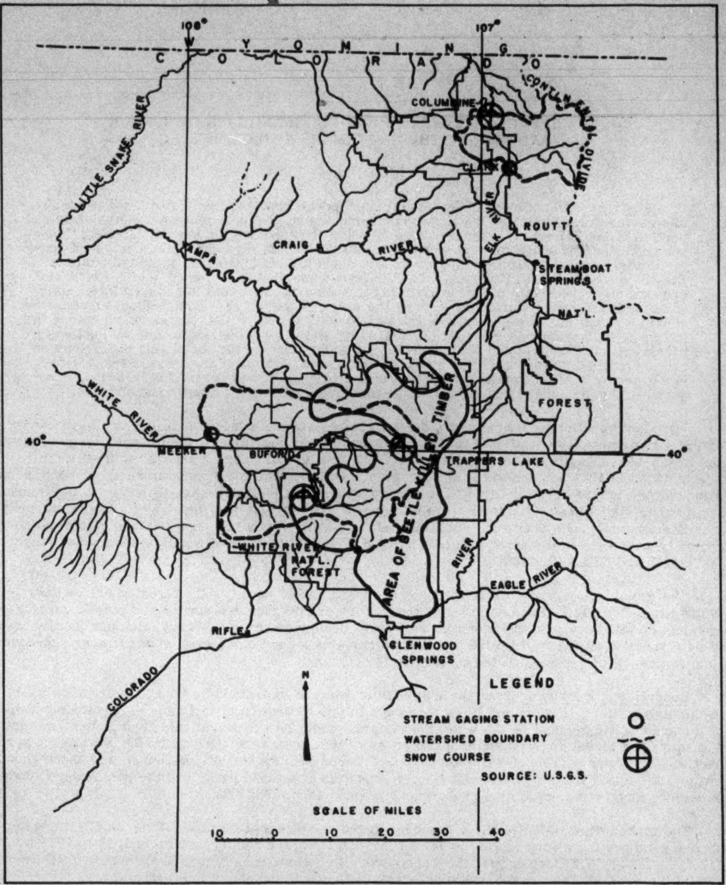
The Engelmann spruce beetle outbreak occurred on 226 sq mi of the forested area within White River drainage. The beetle killed the mature and overmature spruce and pine in varying amounts on this area. On the average, dead trees occupy 60 pct of the area, although locally areas of dead trees varied from 26 to 80 pct. There remains a good stocking of young timber reproduction in many of the areas affected by the beetle outbreak.

Description of study areas--The White River Plateau is drained by White River which rises in the plateau itself (Fig. 1) and flows westward to join Green River in Utah. No accurate estimate of the area of timberland on the watershed is available. The best available figures indicate that 400 sq mi are forest covered and that 226 sq mi of this area were affected by the Engelmann spruce beetle. The lower portion of the watershed is covered with sagebrush, oakbrush, and aspen groves, while in the upper portion one-fourth is open mountain grassland parks and the remainder is lodgepole pine, Engelmann spruce, and subalpine fir timberlands (Fig. 2).

The stream flow of White River has been gaged at Meeker, Colorado, since 1934. The watershed area above the gaging station is 762 sq mi. The average annual flow from 1934 to 1951 was 417,711 ac ft or 10.27 inches over the watershed. Elevations range from 6500 to 12,000 ft. The bulk of the area affected by the beetle outbreak is 10,000 ft and above in elevation.

Two snow courses are located on White River drainage [FEDERAL-STATE COOPERATIVE SNOW SURVEYS, 1952]. The Burro Mountain snow course is located 13 mi south of Buford, Colorado, in an open park at an elevation of 9000 ft. The average water content of the snow pack on April 1 was 18.60 inches for the years 1936-1951. The Rio Blanco snow course is located six miles northwest of Trapper's Lake, Colorado, in an open park at an elevation of 8500 ft. The average water content of the snow pack on April 1 for the years 1936-1951 was 15.76 inches.

To estimate the probable effects of the Engelmann spruce beetle outbreak on the stream flow of White River, similar records were obtained for Elk River drainage above Clark, Colorado. Trees on Elk River watershed have not been attacked by the Engelmann spruce beetle.


108°
107°
WYOMING
COLORADO
LITTLE SNAKE RIVER
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CONTINENTAL DIVIDE
CLARK
ELK RIVER
ROUTT
CRAIG
YAMPA
RIVER
STEAMBOAT SPRINGS
NAT'L.
FOREST
WHITE RIVER
40°
MEEKER
BUFORD
TRAPPERS LAKE
40°
AREA OF BEETLE KILLED TIMBER
WHITE RIVER NAT'L. FOREST
RIVER
EAGLE RIVER
RIFLE
GLENWOOD SPRINGS
COLORADO
N
LEGEND
STREAM GAGING STATION
WATERSHED BOUNDARY
SNOW COURSE
SOURCE: U.S.G.S.
SCALE OF MILES
10 0 10 20 30 40

Fig. 1--Sketch map of the Engelmann spruce beetle outbreak on the White River Plateau in northwestern Colorado

The Elk River watershed is approximately 60 mi northeast of White River. Stream flow of Elk River has been gaged at Clark, Colorado, since 1937. The drainage area above the gaging station is 206 sq mi. The average annual flow for 1937-1951 was 223,562 ac ft or 20.34 inches over the watershed. Elevations range from 7500 to 12,000 ft. Most of the area is covered with stands of lodgepole pine, Engelmann spruce, and subalpine fir. Some alpine grassland occurs above 11,500-ft elevation on the high mountain peaks which form the Continental Divide.

One snow course is located on Elk River drainage at the town of Columbine, Colorado, in an open park on the divide between Elk and Little Snake Rivers at an elevation of 8700 ft. The average water content of the snow pack on April 1 was 17.3 inches for the years 1936-1951.

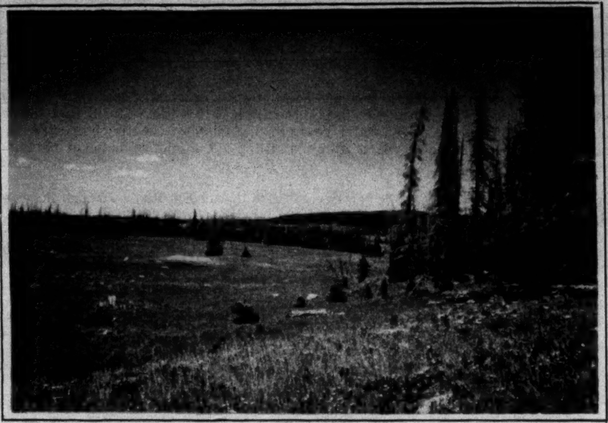

Fig. 2--Dead spruce and pine on the White River Plateau

Table 1 summarizes the annual stream flow and water content of snow on April 1 for the White and Elk River drainages. Stream flow is tabulated for water years beginning October 1 and ending September 30. For example, the water year 1947 begins October 1, 1946, and ends September 30, 1947. The 1947 snow measurement was taken in April, 1947 [U. S. GEOLOGICAL SURVEY].

Table 1--Total annual flow and water content of snow on April 1 for White and Elk Rivers, Colorado

Water year	Total annual flow		Water content of snow on April 1	
	White River	Elk River	White River	Elk River
	inch	inch	inch	inch
1934	6.03	....	....	....
1935	8.99	....	....	....
1936	10.30	....	20.6	21.7
1937	8.11	23.79	15.2	20.3
1938	12.19	26.21	20.8	16.9
1939	9.16	18.48	17.6	14.9
1940	8.86	18.39	13.5	13.2
1941	11.06	17.82	16.6	12.0
1942	11.72	20.38	18.6	14.9
1943	9.28	21.09	14.5	17.3
1944	9.79	19.79	13.2	15.3
1945	11.34	26.34	20.0	22.6
1946	8.94	19.69	12.7	14.2
1947	13.62	23.76	18.5	14.7
1948	11.30	19.43	19.2	18.0
1949	12.86	26.54	22.9	23.4
1950	10.56	22.60	15.7	18.2
1951	10.83	21.21	15.0	19.4

Effect of death of trees--Examination of the records in Table 1 indicate that, on the basis of the general relation between stream flow and water content of snow, the flow of White River increased slightly during the 1941-1946 water years and that a larger relative increase occurred after 1946. These increases coincide with the history of the Engelmann spruce beetle outbreak. The outbreak began in 1941 and had run its most active course by 1946.

To facilitate analysis, the stream flow and snow storage records of the White River drainage were divided into the following three periods: (1) the 1934-1940 water years before the killing of the spruce and pine; (2) the 1941-1946 water years during which the beetle outbreak was most active; and (3) the 1947-1951 water years after the killing of the mature and overmature spruce and pine had been completed.

It appears that the flow of White River is related to that of Elk River through the general similarity of climate on the two drainage basins, but the differences in flow are caused in part by the character of individual storms which result in differential snow deposits. Because the snow courses on the White River watershed are in open parks, they were not affected by the death of the trees, and the beetle outbreak caused no difference in the snow-course measurements on the two watersheds.

Using the data in Table 1 for the ten years, 1937-1946 inclusive, before killing of spruce and pine was completed, the regression equation which follows was fitted by the method of least squares [SNEDECOR, 1946, p. 342].

$$Y = 3.8849 + 0.28897x_1 - 0.33931x_2$$

where Y = estimated annual flow of White River, x_1 = annual flow of Elk River, and x_2 = difference (Elk minus White) in the April water content of snow on the two watersheds. The multiple correlation coefficient $R = 0.8847$ is highly significant and the standard error of estimate is 0.746 inch. The regression coefficients of x_1 and x_2 are also highly significant.

Thus the regression equation for the ten years 1937-1946 provides close estimates of the White River flows. If no change had taken place in the White River watershed, it would be expected that the observed flows of White River for the ensuing years 1947-1951 would be approximately equal to those estimated from the equation. The differences in observed and estimated flows measure the effect of the dead trees on stream flow. A summary of the differences in estimated and observed flows of White River is given in Table 2.

Table 2--Estimated and observed annual flows of White River for water years 1947-1951

Water year	Estimated flow	Observed flow	Difference
	inch	inch	inch
1947	12.06	13.62	+1.56
1948	9.91	11.30	+1.39
1949	11.38	12.86	+1.48
1950	9.57	10.56	+0.99
1951	8.52	10.83	+2.31

Observed flows exceed estimated flows in every year, and the average excess of 1.55 inches was highly significant, with confidence limits at the five per cent level of 0.95 to 2.14 inches. The above analysis indicates that the Engelmann spruce beetle outbreak has influenced the stream flow of White River.

By means of the regression equation, the annual flow of White River was estimated for each of the three periods as an additional test of the beetle outbreak on stream flow. An analysis of variance was made of the differences between the observed and estimated flows to determine whether the flows during the three periods were different. This analysis is summarized in Table 3.

The difference shown in Table 3 of 1.22 inches between the mean flows, 1937-1940 and 1941-1946, and of 2.28 inches between 1937-1940 and 1947-1951, as adjusted for climatic fluctuations by the regression equation, are highly significant. The confidence limits of 1937-1940 and 1947-1951 difference of 2.28 inches are 1.64 to 2.92 inches at the five per cent level.

Table 3--Comparison of the differences between observed and estimated flows of White River for three periods

Number of observations	1937-1940	1941-1946	1947-1951
	inch	inch	inch
1	-0.919	+0.465	+1.56
2	-0.592	+0.690	+1.39
3	-0.981	+0.251	+1.48
4	-0.441	+0.899	+0.99
5	.....	+0.726	+2.31
6	.....	-0.126	....
Mean	-0.733	+0.484	+1.55

All differences before 1941 were negative and all since were positive with the exception of 1946. Within the three periods the relation between observed and estimated flows was linear.

Discussion--The analyses reported deal with stream flow as measured at Meeker, Colorado, and indicate that the flow has increased by an amount equivalent to a depth of 2.28 inches over the 762-sq mi White River drainage basin. Because the death of the trees on 226 sq mi of the watershed area is the only change known to have occurred, it is pertinent to estimate the probable increased flow from the area of beetle-killed timber. To obtain the increased flow indicated by the analyses, 7.68-inch depth would be required on the 226 sq mi of beetle-killed timber.

The probable reasons for the indicated increase in water yield are reduced interception and transpiration. The beetle-killed trees are still standing and retain a large proportion of their branches, but the loss of foliage and finer branches allows more snow to reach the ground (Fig. 3). However, the beetle-killed areas are not comparable to complete openings in the stands because the dead trees still protect against complete exposure to Sun and wind.

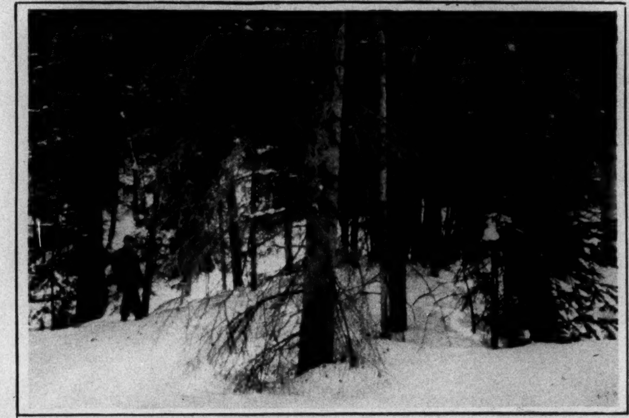

Fig. 3--Snow interception is reduced by the death of the spruce and pine; contrast snow depression in the foreground with one under live tree (right), April, 1953

It is possible that some factor (or factors) not associated with the death of the trees is responsible for the change in stream flow, although this does not seem likely because of the lack of change in the flow of Elk River. More detailed records of snow pack over the watershed and air temperatures during the snowmelt period would permit more rigorous analyses, but such records are not available.

While the evidence indicates that the death of the spruce and pine trees has caused an increase in water yield, the Engelmann spruce beetle is not the most effective or economic method of controlling the density of timber stands. Experiments in the spruce-fir and lodgepole pine forest types on the Fraser Experimental Forest have shown how certain timber harvesting methods may increase water supplies [WILM and DUNFORD, 1948; GOODELL, 1952]. Through planned timber harvesting in spruce-fir and lodgepole pine types, stream flow can be increased without the waste of the timber resources, danger of snagfed forest fires, and the risk of soil erosion associated with the catastrophic outbreak of the Engelmann spruce beetle.

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DETECTING HYDROLOGIC EFFECTS OF CHANGES IN WATERSHED CONDITIONS BY DOUBLE-MASS ANALYSIS

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Abstract--Double-mass plotting of hydrologic events against a meteorological control is one way of detecting the effects of changes in watershed condition. This method of plotting showed what changes in sedimentation and peak inflow were associated with the occurrence of wildfires in the watershed above Gibraltar Reservoir, Santa Ynez Watershed, California. A meteorological control was calculated from the maximum daily precipitation of a storm and the precipitation during an antecedent period. Sedimentation of the reservoir and peak inflow were found to have increased markedly following the wildfires of 1932 and 1933, then to have decreased as the watershed recovered from the fires. No change in the total annual inflow was detected using the same method. The effects of changes in watershed condition must be taken into account in estimating long-term average sedimentation and flood frequency from the short-term records now available.

Introduction--A record of hydrologic events measured at one place over a period of time presents the following question to the hydrologist: Are the data all really comparable throughout the period of record? If the data are not comparable, some adjustment of the data may be necessary before estimating a mean or a frequency.

A simple method of detecting the need for adjustments in data and of making the adjustments was introduced by MERRIAM [1937]. The method is 'double-mass' analysis. Illustrations of the use of the method are found in LIGHT and KOHLER [1943], KOHLER and LINSLEY [1949], KOHLER [1949], LINSLEY, KOHLER, and PAULHUS [1949], TENNESSEE VALLEY AUTHORITY [1951], and OLTMAN and TRACY [1951]. The method seems particularly appropriate for use in detecting the hydrologic effects of changes in watershed condition because both variation in the effects with time and lag in effects may occur. The method may also be used for testing some specific hypothesis of the expected hydrologic effects of changes in watershed condition.

This paper illustrates double-mass analysis of the consistency of the records of peak inflow, total annual inflow, and sedimentation of Gibraltar Reservoir. The reservoir is located in the Santa Ynez River Watershed, California, which is the source of water supply for the city of Santa Barbara.

Double-mass analysis--The double-mass technique consists of plotting some hydrologic event being tested for inconsistency in time against a control. By inconsistency is meant that some non-random change occurred at some time during the period of record in either (1) the magnitudes of the events being tested, or (2) the method by which the magnitudes of the events were computed. Either may be detected and evaluated if the other was consistent.

Some basic requirements for valid application of the 'double-mass' method should be listed:
(1) The control variable must be consistent during the period of record.
(2) The hydrologic event being studied must be highly correlated with the control.
(3) If the data are not consistent in time, any single analysis should include only events in which the change is approximately proportional to the size of the event.

Test of the control--The test of precipitation records for Juncal rain gage (Fig. 1) is the first step in the study of the consistency of the peak inflows, total annual inflows, and sedimentation records of Gibraltar Reservoir during a period when inconsistency might have occurred because of the effects of large wildfires in the watershed. The controls used were functions of the precipitation measured at two gages in the watershed, the Juncal gage and the Gibraltar gage. Figure 1 shows that the precipitation measurements at Juncal were consistent in time. A similar double-mass test of the Gibraltar precipitation gage showed that it too had been consistent in time. Therefore, it was concluded that the average of the precipitation measured at these two gages was suitable, as far as time consistency was concerned, for use in calculating a control variable.

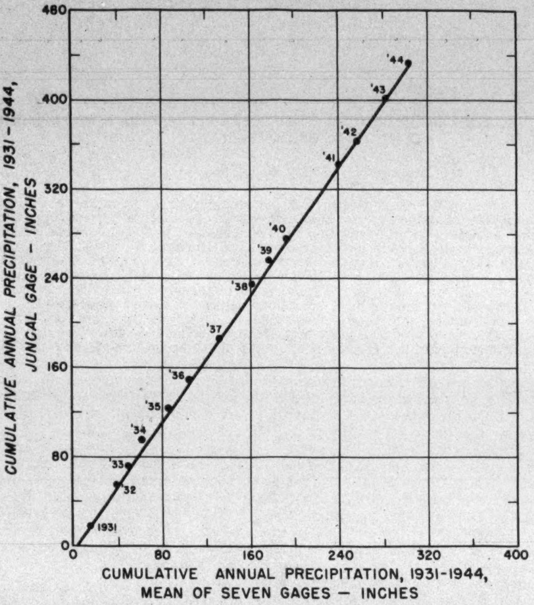

Fig. 1--Double-mass test of the consistency of precipitation measured by the Juncal gage during 1931-1944; the seven gages used in the control were Santa Maria, Santa Barbara, Rancho Sespe, Choro Grande, Ozeno, San Julian, and Selby Ranch

Consistency of peak inflows--One hydrologic event being tested was the maximum yearly peak inflow into Gibraltar Reservoir during the period 1931-1947. The control was a calculated variable called the 'precipitation effectiveness.' The control values were computed from two precipitation variables: the maximum daily precipitation P which is an index of storm intensity; and the precipitation occurring in the 21 days antecedent to the maximum day aP which is an index of the watershed wetness when the storm causing the peak inflow occurred. The function $P^{1.87} \times aP^{0.47}$ combines the two precipitation variables in a way which is highly correlated with peak discharges [ANDERSON, 1949, eq. 2, p. 571].

The middle trend line of Figure 2 shows a plotting of the precipitation effectiveness for the storm which produced the peak discharge of each year, plotted cumulatively against the measured peak discharges. The slope of the line indicates the relative discharge for a year; the changes in slope indicate the inconsistency in peak discharges in the period of record. The relative discharges at the start of the record are indicated by the part of the trend with slope of 1.00, then the slope becomes 2.10, reaches a maximum of 4.40, and declines to 2.80, 1.52, and 1.22.

The fire history in the watershed during the same period is shown by the upper trend line in Figure 2. Large fires occurred in the watershed in 1932 and 1933, the total area of both fires equaling 31 pct of the watershed. The figure shows no detectable change in the peak discharge for the 1933 water year, the first year after the 1932 fire. However, after 1933 the peak discharges increased markedly, the greatest increases occurring the first five years after the fires and lesser increases occurring in succeeding periods. The double-mass method is probably the simplest way of detecting the effects of changes in watershed conditions when both complex time variation and lag are likely to be involved.

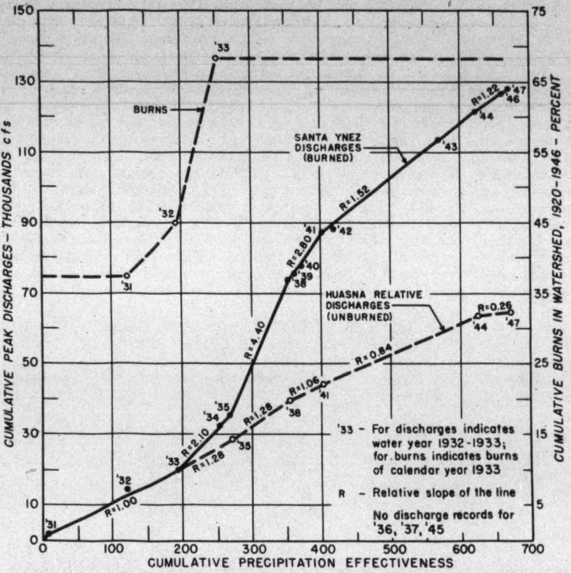

Fig. 2--Double-mass test of the consistency of annual peak inflows of the Santa Ynez River at Gibraltar Reservoir (drainage area 219 sq mi), with the associated watershed fire history, 1931-1947; also shown are the relative discharges for the unburned Huasna River Watershed (drainage area 119 sq mi) for corresponding periods

What happened to peak discharges during the same period in other watersheds in the area that had not been burned recently? The peak discharges of the Huasna River, about 50 mi away and long unburned, were plotted using the same method and the same periods. The precipitation effectiveness in this test was calculated from a single rain gage at Santa Maria, outside the watershed. Despite rather wide fluctuations of the points, the trend is essentially linear.

To permit visual comparison of this long-unburned watershed with the one recently burned, the slopes obtained for the unburned watershed were plotted on Figure 2 for corresponding periods. The slopes are shown as the lower trend line in the figure. The relative discharges of the unburned watershed are seen to persist at about the same slope throughout, whereas the relative discharges of the burned watershed showed wide deviations from the pre-burn slope for a number of years after the fires. One can conclude, therefore, that the increases in peak discharges in the Gibraltar watershed were due to the fires.

It will be recalled that one requirement for double-mass testing is that if the data are not consistent in time, only events in which the change is approximately proportional to the size of the event should be used. Inspection of the line-up of individual points of the middle trend line in Figure 2 indicates that the large peaks of 1938 and 1943 and the smaller peaks of proximate years were similarly affected by the fires in the watershed. Had the different sizes of peaks not been similarly affected, the changes in slopes would have represented averages of the several effects.

Wide fluctuations in peak discharges, such as were found in this test to be associated with watershed fires, must be taken into account before such discharges can be used to determine flood frequency. The double-mass technique provides a means for making adjustments of the discharges measured before and after fires, the basis of adjustment being the changes in the slope of the relative discharge lines.

Probably the most common adjustment of discharges will be the adjustment to the expected values under an average burn condition. Such an adjustment of the Gibraltar peak discharges will be illustrated. First, what is the average expected burn condition? A study of recent fire history in a large area similar to the Gibraltar watershed indicates an average expected burn equivalent to 1.44 pct of the area annually. Of course, the burns do not usually occur as small annual burns but as occasional large burns followed by a period of years without burns. An example is the fire history in the Gibraltar watershed, where the large burns of 1932 and 1933, totaling 31 pct of the watershed area, were followed by no burns for the next 18 years. The next step is to choose a period for the Gibraltar watershed such that the average annual burn in the period will equal the 1.44 pct of the watershed area. Based on the 31 pct burn in the two years, 1932 and 1933, an average annual burn of 1.44 pct would be equivalent to such burns occurring at an interval of about 21 years. Thus, the 21-year period 1933 to 1953 is taken as a period with representative burn conditions in the Gibraltar watershed. The average relative discharge for this period 1.86 is the arithmetic average of the relative discharges read from Figure 2 (using extrapolated values where necessary). The ratio of this average relative discharge 1.86 to the relative discharge for any individual year is the adjustment factor for that year's discharge. The adjustment of the recorded peak discharges for the years 1933 to 1947 to their expected values under average burn conditions is shown in Table 1.

Table 1--Adjustment of recorded peak discharges for 1933 to 1947 to their expected values under average burn conditions

Water years	Peak discharge	Relative discharge[a]	Adjustment factor[b]	Adjusted discharge
	1000 cfs			1000 cfs
1933	5.8	1.00	1.86	10.8
1934	12.5	2.10	0.89	11.1
1935	3.4	2.10	0.89	3.0
1936	. . .	(2.10)[c]	0.89	. . .
1937	. . .	(4.40)	0.42	. . .
1938	38.2	4.40	0.42	16.0
1939	1.3	2.80	0.64	0.8
1940	2.0	2.80	0.64	1.3
1941	9.8	2.80	0.64	6.3
1942	0.6	1.52	1.22	0.7
1943	25.6	1.52	1.22	31.2
1944	8.3	1.52	1.22	10.1
1945	. . .	(1.22)	1.52	. . .
1946	4.8	1.22	1.52	7.3
1947	1.4	1.22	1.52	2.1
1948-1950	. . .	(1.11)	1.67	. . .
1951-1953	. . .	(1.00)	1.86	. . .
Average 1933-1953		1.86		

[a] From Figure 2.

[b] Equivalent factor for 1.44 pct burn, 1.86, divided by relative discharge.

[c] Parentheses indicate number was extrapolated.

The adjusted discharges are, then, those that would be expected under the average burn condition determined for this area.

Consistency of total annual inflows--Annual undepleted flows of the Santa Ynez River at Gibraltar Dam for the water years 1921 to 1948 [U. S. DEPARTMENT OF INTERIOR, 1948] also were plotted double mass against a control calculated from precipitation records. The control is the least-squares equation $Q = 6.504\ P_o + 0.623\ P_1 - 68.59$, in which Q is the calculated annual runoff in 1000's ac ft; P_o is the annual precipitation during the same year (mean of Santa Barbara and Ozena gages), in inches; and P_1 is the annual precipitation during the first year antecedent to the runoff, in inches. The standard error of estimate is ± 15,130 ac ft. Figure 3 shows the results of the test of annual flows plotted in the lower curve, with the fire history shown in the upper curve. The test did not indicate any change in the total annual flows associated with the fires in the watershed. The

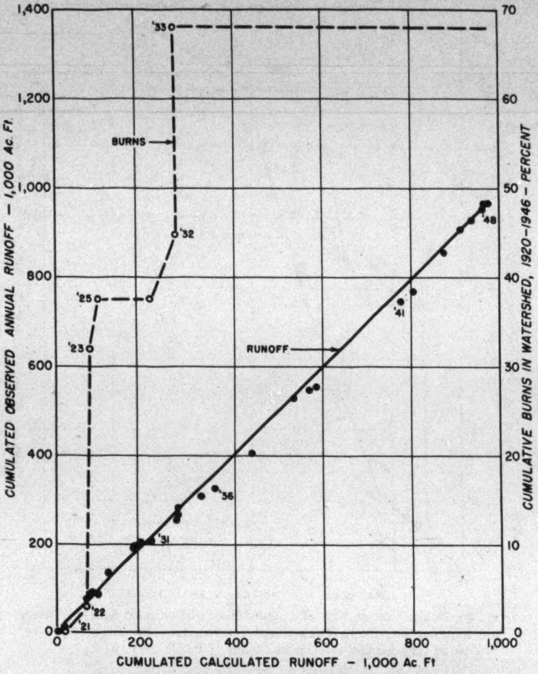

Fig. 3--Double-mass test of the consistency of total annual inflows of the Santa Ynez River at Gibraltar Reservoir, with associated watershed fire history, 1921-1948

idea that significant amounts of water may be saved simply by burning off the brush, therefore, appears open to serious question in this area.

Consistency of reservoir sedimentation--The method used for the sedimentation study was the same as for the peak discharge study. In calculating a control variable, the same two precipitation variables were used: the maximum daily precipitation of a storm P, and the 21-day precipitation antecedent to the storm aP. These were combined to form a control variable which had been found to be highly correlated with sediment production, $P^{1.62} \times aP^{0.41}$. P and aP are for the maximum storm of each year [ANDERSON, 1949, eq. 4, p. 581]. This control variable, the precipitation effectiveness, was used as an index of the sediment-producing potential for a year. Starting with the first year after construction of Gibraltar Dam, the precipitation effectiveness of each year was calculated. These were plotted cumulatively against the measured periodic sedimentation of the reservoirs in the watershed. Sedimentation was the sum of deposition in Gibraltar and Juncal Reservoirs and Mono and Caliente debris basins. The cumulative wildfires in the watershed are shown on the same graph (Fig. 4).

In the lower trend line of Figure 4, the relative sediment production of the 1920-1931 period is seen to be an average of sedimentation under both unburned and burned conditions, with the relative sediment production for the whole period being taken as 1.00. The additional effects of the 1932 and 1933 fires are shown as increases in the relative sedimentation to 2.68 and 3.87 during

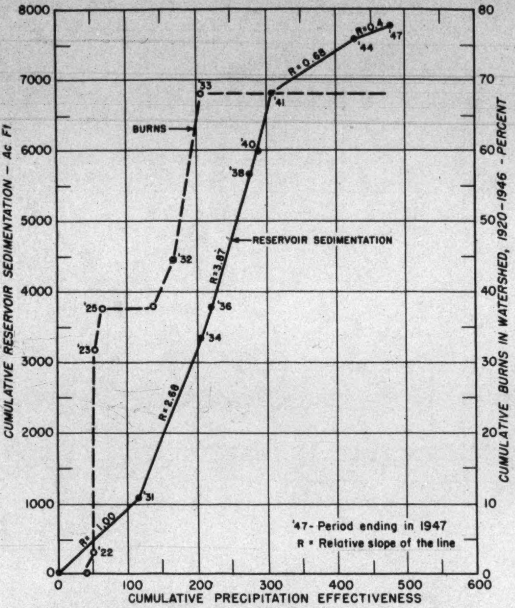

Fig. 4--Double-mass test of consistency of periodic sedimentation of reservoirs, Santa Ynez River above Gibraltar Dam, with associated fire history in the watershed, 1920-1947

the first eight years after the fires, followed by a general decline in sediment production in the ninth and subsequent years. It might be well to note that adjustment for 'trap efficiency' [BRUNE, 1953] would not appreciably affect the slopes of the lines.

It is concluded that such marked influences of fires on sedimentation may make it necessary to adjust for the coincidences of large storms and fires before estimating average annual expected sedimentation of reservoirs. The effects of fires detected by the double-mass technique permit such adjustments to be made, using methods similar to that illustrated for adjusting peak discharges.

Use of double-mass technique in hypothesis testing--It should be noted that the double-mass method has the limitation that only the net effect of the relationship of 'deterioration' to 'recovery' is shown. For example, in Figure 4 if the watershed during the years 1931-1934 was still recovering from the effects of the 1923 and 1925 fires, then the increase in relative sedimentation indicated for the 1931-1934 period is less than the total effect of the fire. Therefore, the full effect of several fires occurring at intervals probably cannot be detected by this method. This limitation of the method applies only to the hypothesis formulation stage of studies, for which watersheds with a single burn or a single 'treatment' should be used. Once a hypothesis has been formed, the double-mass method may be used to test that hypothesis, even using watersheds with complicated 'treatment' conditions. For example, studies in the nearby San Gabriel mountain watersheds indicated that the sedimentation varied as the - 1.97 power of the cover density [ANDERSON, 1949, eq. 4, p. 581]. The hypothesis is that this cover function is applicable to the Gibraltar watershed. By combining the cover function with the precipitation effectiveness and double-mass plotting against measured sedimentation, the hypothesis was tested. If the combination explained all the variation, the deviations in slope from 1.00 in the trend line of Figure 4 would be removed. But inclusion of the cover function removed only two-thirds of the deviation in the trend of the 1931-1934 period from that of the earlier period. Therefore, this test indicates that this cover function was not fully applicable to the Gibraltar watershed; burning apparently had a greater effect on sedimentation than would be indicated by that function. It is quite possible to test hypotheses of the expected effects of other factors on sedimentation, such factors as changes in reservoir trap efficiency, consolidation of sediments, and annual runoff. The method has the advantage that it allows the analyst to see how the hypothesis is working out. Deviation from expected results furnishes a basis for revision of hypotheses, which revisions may easily be tested in other watersheds by the double-mass technique.

Data are available in most areas of the United States for making many such tests. In California alone there are some 250 watersheds with more than 20 years of stream-flow records; recently records of sedimentation of 92 California reservoirs were published, and suspended sediment records for some 170 streams are available [FEDERAL INTER-AGENCY RIVER BASIN COMMITTEE, 1949, 1952, 1953]. Region by region, the double-mass technique should be of help in detecting the effects of watershed condition and other variables on hydrologic events and providing a basis for making proper adjustments in these data before using them to determine a mean or a frequency.

Summary and conclusions--The applicability of the double-mass plotting technique to detection of hydrologic effects of changes in watershed condition was explored. Using this technique, peak discharges, total annual discharge, and reservoir sedimentation before and after large brushland fires in a watershed were compared.

The rates of sedimentation and of peak inflow into Gibraltar Reservoir, near Santa Barbara, California, were markedly increased for several years following the occurrence of wildfires in the watershed. No change in total annual inflow was detected.

The influence of wildfires or other watershed changes must be evaluated and adjustments made before using the historical record of sedimentation or peak discharges to estimate a mean or a frequency. Double-mass analysis provides a basis for making such adjustments.

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AN INVESTIGATION OF THE FREEZING OF WATER IN CAPILLARIES

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(Pennsylvania State University Contribution No. 53-22)

Abstract--In order to isolate the factors governing the freezing point of cloud and precipitation elements, experiments have been made to measure the effects of physical dimension and of certain ions in solution upon the freezing temperature of water in glass capillaries. The results of these experiments indicate that the freezing point of water in capillaries is independent of the volume or of the interface area, and that the radius of the capillary tubing is the only physical dimension that affects the freezing point of water contained in it. The amount of supercooling necessary to induce freezing can be either increased or diminished by the addition of certain ions in solution. The magnitude and sign of the change in freezing point are functions of the type of ions in solution, the molar concentration of the ions, and the capillary radius.

Introduction--Water in small quantities can be quite easily cooled below the melting point of ice. In quantities as large as several cubic centimeters, supercooling of as much as six degrees centigrade can be accomplished with no special precautions other than that the ice phase must be absent at the start. Small water droplets can be supercooled to a greater degree than bulk water. Investigations by MOUSSON [1858], DUFOUR [1863], HEVERLY [1949], and DORSCH and HACKER [1950] have demonstrated that the smaller the diameter of water droplets, the lower the spontaneous freezing temperature. According to TURNBULL [1950], the degree of supercooling necessary to cause crystallization of liquid metals is dependent upon droplet size in the same manner. Analogous results from tests employing capillaries have been reported by DESPRETZ [1837], SORBY [1859], KOCHS [1892], BAHMETIEV [1900], BOROVIK-ROMANOVA [1924], and LANGE [1930]; the smaller the diameter of a glass capillary, the lower the spontaneous freezing point of the water specimen in it. All these experiments seem to indicate that some physical dimension of the water specimen plays an important role in determining the freezing temperature.

Droplet or capillary diameter is the dimension correlated with freezing point in all of the cited works. However, no indication is given as to whether it is the diameter that affects the freezing point, or the volume, or the interface area, all of which are functions of diameter. This has led to speculation regarding the reason for the observed experimental results. LEVINE [1950] has suggested that freezing is due to the presence of 'motes' as explained by DORSEY [1948], or the formation of a critical nucleus as proposed by VOLMER [1939]. He contends that, since the probability of the existence of a mote or critical nucleus in a droplet is a function of volume, a statistical summary of freezing data for various drop sizes should show that the mean freezing point of small drops will be lower than that for large drops. The probability that a mote will be present, or that a critical nucleus will be formed is greater in large drops than in small drops. One would expect that of a large number of small drops, at least one would contain a mote that would cause it to freeze at the same temperature as observed for large drops. In other words, the extreme freezing temperatures for a given drop-size range should be essentially independent of the drop size for a large population. Inspection of DORSCH and HACKER's [1950] curves shows that the maximum and minimum freezing temperatures run roughly parallel to the curve showing the mean freezing temperature versus drop diameter.

A current study of the freezing of water has included the following investigation: (a) the freezing of droplets in clouds; (b) the freezing of droplets deposited on a surface; and (c) the freezing of water in capillaries. The last of these offered the best possibility of controlling the several factors that might affect the freezing point of water. Volume, interface area, and radius could be independently varied. Capillaries were also used extensively when the effect of known concentrations of foreign materials in water was to be tested. The results of the capillary phase of this cloud physics study are presented in this paper.

Method of investigation--Distilled water was obtained from the analytical chemical laboratories at Pennsylvania State University and kept in a large glass-stoppered bottle; all the water used in the experiments reported here was drawn from this source. New Pyrex capillary tubings were placed in chromic acid cleaning solution for 12 hr and subsequently in distilled water for another 12 hr. The tubes were then thoroughly washed by forcing distilled water through them and dried before use. In a few special experiments, chromic acid was not employed; in these cases the tubes were thoroughly rinsed with distilled water. The differences between freezing points obtained with and without the prior use of the cleaning agent were very small. Tubes were re-used only for determination of the freezing point of distilled water. Following the introduction of water into the capillaries, the ends were dried and sealed to prevent movement of water and to eliminate the possibility of nucleation by the ice phase.

The temperature of the water in the capillary was measured with a copper-constantan thermocouple made of no. 40 wire connected to a mirror galvanometer. One junction was placed inside the capillary tube, approximately one to three millimeters from the water sample. The time required for cooling a specimen varied from ten to 25 min; subsequent experiments showed that variations in the rate of cooling within the limits encountered did not affect the freezing point.

The moment of freezing was noted quite readily by placing a mirror under the capillary and observing the light transmitted through the water (Fig. 1a). Upon freezing, the water became more opaque to light; the resulting change was quite pronounced and easily discernible (Fig. 1b). In most cases freezing occurred in a fraction of a second, in which the entire mass immediately changed to ice.

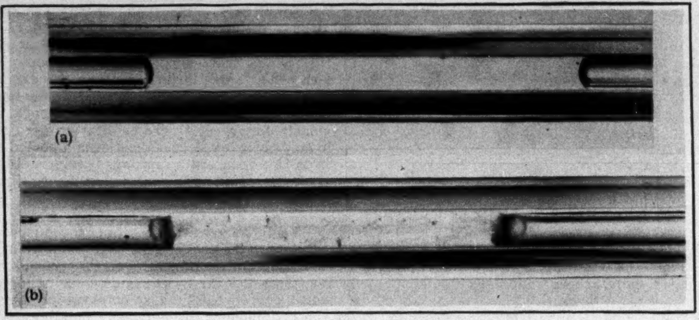

Fig. 1--View of the three-millimeter tube (a) liquid water at -10°C; (b) ice formed at -14°C

Table 1--Summary of test runs using distilled water

Capillary diameter	Mean T_{sf}[a], σ, and N for various parameters held constant																	
	Volume, 39.6 mm			Length, 10 mm			Glass-water interface area			Diameter[b]			Length equal to diameter			Summary of all runs		
	Mean T_{sf}	σ	N	Mean T_{sf}	σ	N	Mean T_{sf}	σ	N	Mean T_{sf}	σ	N	Mean T_{sf}	σ	N	Mean T_{sf}	σ	N
mm																		
6	....	...	..	-12.1	2.6	40	....	...	..	....	...	..	....	...	..	-12.1	2.6	40
4	....	...	..	-13.3	2.4	40	....	...	..	....	...	..	....	...	..	-13.3	2.4	40
3	-12.9	1.4	68	-13.1	0.8	10	-13.3	1.4	7	-13.3	0.2	6	-13.8	1.3	5	-13.0	1.3	96
2	-15.6	0.9	65	-15.9	1.6	10	-15.7	1.3	10	-16.2	0.9	15	-15.4	1.1	5	-15.7	1.0	105
1	-18.7	1.8	56	-20.4	1.8	10	-18.5	0.8	11	....	...	..	-18.2	0.7	5	-18.9	1.7	82
0.75	....	...	..	....	...	..	....	...	..	-21.3	2.0	30	....	...	..	-21.3	2.0	30
0.50	....	...	..	-25.5	3.1	40	....	...	..	....	...	..	....	...	..	-25.5	3.1	40
0.25	....	...	..	-27.8	2.2	30	....	...	..	-27.5	2.5	15	....	...	..	-27.7	2.3	45

[a] T_{sf} denotes temperature of spontaneous freezing; σ, standard deviation; and N, number of runs.

[b] Length varied from one to 102 mm.

Results using distilled water--In Table 1 the results of five sets of experiments are summarized. Volume, length, and the area of the glass-water interface were held constant, while the capillary diameter was varied. Moreover, the capillary diameter was held constant and the length of the water sample was varied from one to 102 mm, thus varying the volume and the glass-water interface area. It appears that the only factor influencing the freezing point is the diameter of the capillary.

Figure 2 is a graphic summary of all data using distilled water. The maximum, mean, and minimum freezing points for water in each capillary size is shown. The trend in all three curves is striking. The scattering of the freezing point of specimens contained in a given size capillary is small. No water sample contained in a 0.25-mm capillary froze at a temperature as high as the lowest temperature at which specimens contained in a capillary of two or more millimeters froze. This appears to be contrary to the hypothesis that the freezing point depends upon the probability that a mote is contained in a given volume of water.

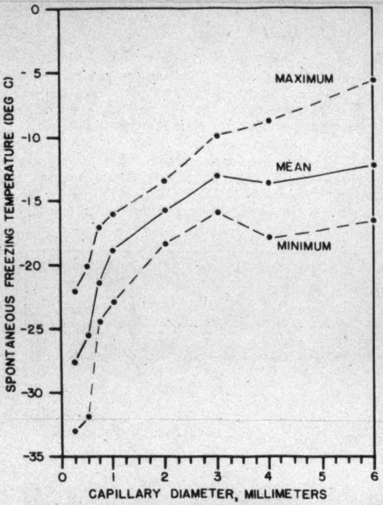

Fig. 2--Variation of spontaneous freezing temperature with capillary diameter

To be certain that the area (or other dimensions of the air-water interface) was not responsible for the results, a separate series of experiments was made using capillaries tapered at both ends. Here, the area of the air-water interface was reduced considerably, while the largest inside diameters were the same as those previously employed. These capillaries were cooled in steps of a few degrees and over a period of 15 to 30 min in order that large temperature gradients would not be present in the water due to varying capillary thickness.

Table 2 shows the results of these runs together with the corresponding freezing points for capillaries with uniform bores (in parentheses). It appears that the spontaneous freezing temperatures correspond to those obtained for samples in ordinary capillaries with diameters equal to the central diameter of the tapered capillary. Also, on several occasions, the freezing was noted to start near the center of the capillary, although in most cases the speed of crystallization prohibited an accurate determination of the direction of the freezing progress. This is in contrast to the observations of capillaries with untapered bores; on those occasions when the direction of freezing progress could be noted, it was from one end of the water sample to the other. In the case of untapered capillaries, the place of initial freezing is probably dictated by the greater rate of heat loss from the end of the sample, where the freezing starts. In the tapered capillaries, although the distribution of heat loss along the tube would also necessitate initial freezing at the ends, freezing was often observed to start in the central portion of the water sample. This testifies to the importance of the diameter of the water sample in determining the spontaneous freezing point.

Table 2--Variation of air-water interface area

Central capillary diameter	Menisci diameter	T_{sf}	σ	N
mm				
3 (- 13.0)	0.75 (- 21.3)	- 14.2	1.3	10
1 (- 18.9)	0.50 (- 25.5)	- 20.3	1.7	10
0.5 (- 25.5)	0.20 (- 27.7)	- 23.9	2.0	10

Results using water with foreign ions in solution--The same experimental procedure was followed as previously outlined, except that chromic cleaning solution was not employed and new capillaries were used for each solution. All samples were approximately one centimeter in length. Ten freezing temperatures were obtained for each solution and each capillary size. The standard deviations of the spontaneous freezing temperatures of the solutions contained in a given size capillary were of the same magnitude as those obtained for distilled water.

Table 3 shows the deviations of the mean spontaneous freezing temperatures for various solutions from those of distilled water as summarized in Table 1. The spontaneous freezing point of water containing minute amounts of any of the iodides used is markedly higher. Silver nitrate and, particularly, silver sulfide were also found to be very effective in raising the spontanecus freezing temperature. An interesting feature is the fact that the most pronounced effect was obtained with solutions in the smaller capillaries. Silver iodide had a tendency to be more effective in raising the spontaneous freezing temperature after the solution had aged for several days. This might possibly be attributed to the very slow rate of solution of this chemical.

Table 3--Deviations of the mean spontaneous freezing temperatures of various solutions from those obtained with distilled water

Solution	Molar concentration	Capillary diameter			
		3 mm	1 mm	0.5 mm	0.25 mm
		°C	°C	°C	°C
I_2	5.0×10^{-3}	+ 4.6	+ 5.8	....	+ 12.8
Cu_2I_2	7.8×10^{-2}	+ 5.0	....	....	+ 12.8
CdI_2	6.6×10^{-2}	+ 7.4	+ 5.7	+ 11.2	....
PbI_2	2.7×10^{-5}	+ 5.5	....	....	+ 8.2
TlI	3.8×10^{-5}	+ 4.6	....	....	+ 12.7
KI	7.4×10^{-3}	+ 2.4	+ 6.0	....	+ 14.5
NH_4I[a]	8.3×10^{-3}	+ 4.9	+ 9.2	+ 16.9	+ 14.4
AgI	3.3×10^{-8}	+ 1.7	....	....	+ 11.1
$AgNO_3$	1.6×10^{-2}	- 0.1	+ 0.3	....	+ 8.3
Ag_2S	6.6×10^{-20}	+ 2.5	+ 8.0	....	+ 13.6
$CaCl_2$	2.3×10^{-3}	+ 0.5	....	....	+ 0.7
NaCl[b]	4.4×10^{-3}	- 0.6	- 0.7	- 1.1	- 1.1

[a] See Figure 3.
[b] See Figure 4.

The mean spontaneous freezing temperatures obtained with different concentrations of ammonium iodide are shown graphically in Figure 3. Very dilute concentrations of ammonium iodide raise the spontaneous freezing point, the effect being most pronounced in the smaller capillaries. As the concentration is increased, the freezing point is further raised until a critical concentration of the solute is reached; then a sharp decrease in the freezing point occurs for all three sizes of capillaries. This critical concentration of ammonium iodide solution is of the order of 4×10^{-1} M.

For comparison, similar tests were made with sodium chloride (Fig. 4). The spontaneous freezing temperature was not significantly raised in any concentration of this solute in capillaries of 0.5, 1, and 3 mm diameters. At the higher concentrations, the freezing point was lowered.

Results; changes of interface--Since the nature of the interface may also play a role in determining the freezing point of water in capillaries, several coatings on the inside of capillaries were tested to determine the extent of this effect.

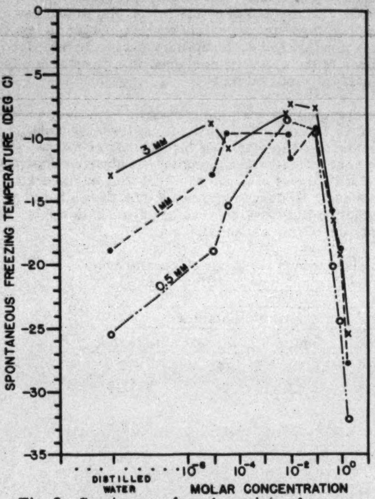

Fig. 3--Spontaneous freezing points of ammonium iodide solution of different concentrations in 3, 1, and 0.5 mm glass capillaries

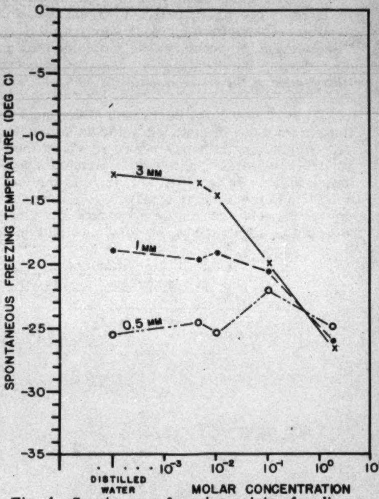

Fig. 4--Spontaneous freezing points of sodium chloride solution of different concentrations contained in 3, 1, and 0.5 mm glass capillaries

Two hydrophobic coatings were employed. One was produced by allowing capillaries to soak in a ferrous ammonium sulfate solution for two days; the tubes were subsequently rinsed with distilled water and then immersed in a soap solution for ten minutes, resulting in a hydrophobic stearate coating. The other coating, a silicone, was produced by treating the capillaries with the commercial product, 'Desicote.' A metallic coating consisting of a film of atomic silver was also used; this film was thin enough to be transparent, thus, enabling observation of the freezing process of the water.

In Table 4, the temperatures represent a mean value for ten runs each. All samples were approximately one centimeter in length. Both hydrophobic coatings lower the freezing point of distilled water; the effect is most pronounced for the samples having larger diameters. By contrast, a silver coating raises the spontaneous freezing point, particularly for water in the smaller capillaries. For ammonium iodide solution, the hydrophobic silicone surface had a smaller effect than with distilled water, lowering the freezing point in the three-millimeter capillary and raising it in the one- and 0.5-mm capillaries.

An explanation of results--Experiments have demonstrated that in the case of water droplets, the freezing point is a function of droplet radius. Experiments have also shown the freezing point of water in capillaries to be a function of capillary radius. The present experiments have shown that it is truly the radius that determines the freezing point, and not surface area or volume. In the case of a tapered capillary the freezing point is a function of the largest radius. It would appear that the increase in supercooling necessary to induce nucleation in small water specimens is a function of the greatest distance any part of the specimen can be from the nearest interface. This distance is equal to the radius in the case of a spherical droplet and for brevity shall henceforth be referred to as the equivalent radius in the case of non-spherical water samples.

At this point it can be stated that the freezing point of small quantities of water is a function of: (a) the equivalent radius; (b) the type and concentration of ions in solution; and (c) the type of surface enveloping the water.

The manner in which these variables affect the freezing point of water in glass capillaries suggests an hypothesis involving the influence of the surface upon the bulk structure of water.

Table 4--A comparison of the mean spontaneous freezing temperatures of samples in coated capillaries with those obtained for samples in uncoated capillaries

Sample	Capillary coating	Capillary diameter		
		3 mm	1 mm	0.5 mm
		°C	°C	°C
Distilled water	None	- 13.0	- 18.9	- 25.5
Distilled water	Silicone	- 20.9	- 23.4	- 28.2
Distilled water	Stearate	- 19.6	- 20.1	- 26.5
Distilled water	Silver	- 11.4	- 11.1	- 13.7
NH_4I solution (1.0×10^{-2} M)	None	- 7.3	- 11.6	- 11.1
NH_4I solution (1.0×10^{-2} M)	Silicone	- 11.3	- 7.9	- 9.0

It is recognized that at solid or liquid interfaces the atomic structure differs from that in the bulk of the solid or liquid. This rearrangement is necessary for the presentation of a surface with a minimum free energy. WEYL [1951] has pointed out that, particularly in the case of water, the realignment in the surface is necessary because of the inability of the protons to adjust their force fields. A proton in the water surface would appreciably raise the surface free energy. An equilibrium surface for water must have the proton slightly recessed in order that oxygen, which has a more flexible force field, lies in the surface. The electron configuration of the oxygen atoms can shift toward the bulk, presenting the smallest possible force field to the surface.

HENNIKER [1949] and HENNIKER and McBAIN [1950] have suggested that in the case of certain liquids, the departure of the surface structure from that of the bulk is not confined to the immediate surface, but may be in evidence to a depth of one or more millimeters. The degree of distortion of the structure at any point in a water sample will be proportional to the distance that the point is from the nearest surface. Hence, samples with small equivalent radii will have greater distortion near the center than those with large equivalent radii.

If we assume homogeneous nucleation is to take place in a supercooled sample of water, one important factor that governs the probability of formation of a critical nucleus is the ability of water molecules to move from the water structure to any incipient crystalline embryo. The influence of any structure imposed upon the water by proximity to the surface would decrease the freedom of the molecules to move about and hence decrease the probability that a critical nucleus would form (see Fig. 2).

The degree of distortion at the surface of the water will be influenced by the type of interface. Therefore, it is not surprising that hydrophopic surfaces cause a lowering of the freezing point, and that any change in interface will cause a change in the freezing point of water samples with small equivalent radii. The magnitude of the change in freezing temperature will depend upon interface characteristics (see Table 4).

If foreign ions are present in the water in high concentration, the structure they impose on the water will make the formation of a crystal nucleus more difficult than in the case of relatively pure water (see Fig. 3 and 4). If, however, the foreign ions are present in very small concentrations, the distortion of the water structure due to their presence will be small. Figure 4 (NaCl solutions) shows clearly the case of ions in solution acting in this manner. For small concentrations the freezing point is very little different from that for distilled water. When the concentration is increased the freezing point is depressed. In Figure 3 (NH_4I solutions), however, small concentrations actually raise the freezing point; but if the concentration is increased, a point is reached where the added distortion due to the ions in solution lowers the freezing point, as is to be expected. The action of the larger and more polarizable ions, in the case of NH_4I in small concentrations, may be either to decrease the amount of distortion at the surface, or prevent the continuation of the surface structure in the interior. It is fairly certain that the large iodine ions will be found in the surface, since they are more capable of reducing the surface free energy than are the oxygen ions. It cannot be stated that the presence of these ions in the surface is sufficient to account for the amount by which the freezing point is raised. Perhaps the large ions exert a cushioning effect and cause a more rapid decrease in distortion with depth than occurs in pure water.

The hypothesis that a distorting influence emanating from the surface is preventing freezing in water masses with small equivalent radii is further supported by the observation that NH_4I causes a greater increase in freezing point for small equivalent radii than for large ones. Water masses with small equivalent radii are more distorted at their center than are larger ones; hence, the amount by which the distortion can be decreased is greater, and thus the amount by which the freezing point is raised is greater. This discussion deals only with ions in solution. In the case of solid suspensions that raise the freezing point of water masses with small equivalent radii, it is likely that the presence of the solid interface results in force fields emanating from the interface which encourage rather than oppose the assumption of an ice-like structure on the part of the water molecules. This oriented overgrowth has been discussed by WEICKMANN [1951].

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DEEP REFLECTIONS FROM SOUTHERN CALIFORNIA BLASTS

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Abstract--Two records showing reflections from the Mohorovicic discontinuity at normal incidence have been obtained from large quarry blasts in Southern California. Each record shows a strong reflection with corrected travel time near 10.6 sec. An earlier reflection appears near 9.0 sec. Strong reflections were also obtained at distances slightly beyond critical. Computations of the thickness of the crust near the quarries have been made using velocity data obtained from blast and earthquake refraction studies. The results using any crustal model that fits the refraction data or by assuming a single-layer crust agree closely. In this area the Mohorovicic discontinuity is 32 km below sea level, and the mean velocity in the crust is 6.2 km/sec. The data give additional evidence for the existence of a zone in which velocity decreases with depth.

Introduction--Extensive studies of the velocities and thickness of the Earth's crust have been made in the past using refracted waves from blasts and earthquakes. Little work has been done using reflected waves despite the fact that they give information complementary to that derived from refraction studies. The principal work has been by TATEL, ADAMS, and TUVE [1953] who have reported the recording of waves reflected from the Mohorovicic discontinuity at critical incidence in many areas of the United States; however, they say that these were not obtained in California due to roughness or absence of the discontinuity. REICH [1953ab] has reported the recording of reflections at normal incidence from the Mohorovicic discontinuity and another shallower discontinuity from two blasts in southern Germany. The presence of a thick sedimentary section under the blasts studied by Reich makes the results less definitive than might be desired, so it was desirable to try recording such reflections at both normal and critical incidence in an area with a minimum of sediments.

The recording of such reflections at normal incidence is important even without reference to the information obtained about crustal velocities and thickness. It has been suggested that the Mohorovicic discontinuity is not an interface but a zone of transition; the recording of normal reflections would establish the abruptness of the discontinuity.

Reflections at normal incidence--Two records of reflections at normal incidence were obtained at the Monolith and Corona quarries as shown in Figures 1 and 2. The Monolith quarry, site of the blast of Figure 1, is located near the top of a hill of recrystallized pre-Cretaceous limestone, surrounded by granitic rocks of the Sierra complex. The blast, on August 1, 1953, consisted of 25 tons of granular 60 pct dynamite. The record was taken on a six-channel exploration seismograph. Six geophones were arranged in a spread nearly radial to the blast at distances of 1115 to 1792 m.

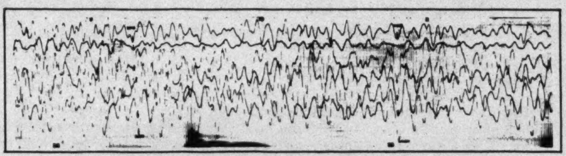

Fig. 1--Portion of reflection record from 25-ton blast at Monolith, California, August 1, 1953; reflections marked at 9.2 and 10.8 sec; second trace inoperative

First arrivals on the multiple-trace record give a velocity of 3.9 km/sec in the limestone, with zero intercept time indicating negligible weathered layer. No break in the travel-time curve occurs, so the limestone body must extend to a depth of at least 500 m below the blast.

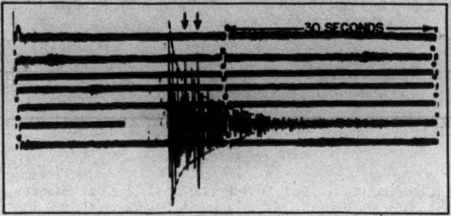

Fig. 2--Record from 60-ton blast at Corona, California, March 31, 1951; peaks of reflected phases marked by arrows

The one definite reflection occurs on the record 10.8 sec after firing time. Timing on the trough of the reflected event gives the data of Table 1.

Table 1--Monolith vertical reflection

Trace	Distance	Geophone elevation	Time	
			Direct	Corrected to elevation of Geophone 1
	km	km	sec	sec
1	1.792	1.234	10.823	10.823
3	....	....	10.823	10.821
4	....	....	10.824	10.821
5	....	....	10.829	10.825
6	1.115	1.257	10.834	10.828

Note: Shotpoint elevation = 1.5 km.

The arrival is earliest on the farthest geophone (recorded on the top line in Fig. 1). Part of this reversal is caused by elevation differences of the geophones; the remainder may be due to variation in the amount of the travel path in the limestone body or to dip in the reflecting horizon. Downward trace motion corresponds to upward ground motion, so the true beginning of this event is at the point where the line on the record begins to turn down. A correction for this and an additional correction to bring the shot and recording points to an elevation of 1000 m to remove the effect of the limestone body give a reflection travel time of 10.59 sec.

No suppresion, automatic volume control, or mixing were used. Because of the lack of the first two, the record is unreadable from the first arrivals to a time of six seconds. Between six and nine seconds there are a few events, the erratic step-out of which brands them probably as random coincidences. There is a possible weak reflection at 9.2 sec; step-out is excessive but can be interpreted as being caused by interference from other energy. The mean travel time of this event, corrected to datum at 1000 m, is 9.02 sec. The record jammed after 34 sec. No events after the phase at 10.8 sec occurred which showed any consistency from trace to trace.

The essentially simultaneous arrivals at all geophones over a 677-m spread give definite proof of the reflective nature of the event at 10.8 sec on the Monolith record. No strong vertical contact at the proper distance exists on either side of the spread to give a side reflection. The possibility of a multiple reflection is not entirely eliminated because the record is unreadable at 5.4 sec. No multiple of order higher than the first is possible because of the absence of events at the proper submultiple times. If this were a multiple, it would imply the existence of a very strong velocity contrast at a depth of about 15 km, and the primary reflection should be strong enough to be easily detected on other blast records of amplitude low enough to be readable at a time of five seconds. No such arrival has been observed.

The Corona quarry is on the side of a hill of quartz latite porphyry within the Southern California batholith. A blast of 60 tons of nitramon was fired March 31, 1951. Other data on this blast have been reported by GUTENBERG [1952]. A record taken on a Benioff short-period variable reluctance vertical seismometer 150 m from the blast is shown in Figure 2. The original faint lines have been reinforced for reproduction. A strong single-cycle event is visible 10.49 sec after the first motion, with motion down on the record. A less outstanding half-cycle event at 8.80 sec has motion up on the record. Direction of initial motion is unreadable, and polarity of the instrument is not known. The travel time for the first arrival through the material in the quarry is between 0.02 and 0.05 sec for any reasonable value of velocity, so the total travel times of the two events are close to 8.8 and 10.5 sec, different by 0.2 and 0.1 sec respectively from the corrected arrival times at Monolith. The elevation difference is 0.65 km, so if the reflecting horizons were at the same level, the time difference should be about 0.4 sec.

The two blasts show arrivals at nearly identical times and no arrivals later. This alone is not sufficient proof that both records show reflections from the Mohorovicic discontinuity; it does imply that the two records represent the same events. The Monolith record shows the event at ten seconds to be a reflection from great depth. The weaker earlier arrivals on both records, separated from the later arrivals by the same time interval, give added evidence that these phases are correlatable. As the Mohorovicic discontinuity is the most pronounced velocity contrast known to exist deep in the crust and no abrupt velocity changes are known to occur in the mantle just below it, a strong reflection from a depth near 30 km followed by no others can be presumed to be from the Mohorovicic discontinuity.

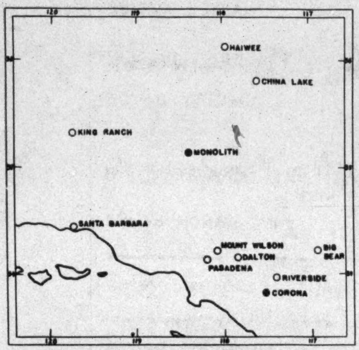

Fig. 3--Map showing location of quarries and seismograph stations discussed

Reflections beyond critical incidence--On theoretical grounds strong reflections are to be expected at and shortly beyond the critical distance for total reflection. Strong second arrivals are found on records from seven of nine stations at distances between 103.9 and 169.0 km from several blasts at Monolith. Station locations are shown in Figure 3; a composite set of these records from the 25-ton blast on August 1, 1953, and a 30-ton blast on September 6, 1952, are in Figure 4. Records taken at the same stations for the two blasts are nearly identical, so combining the data to extend coverage is justifiable. Very strong second arrivals are in contrast with weak first arrivals. The second arrivals are either late or missing at King Ranch and Santa Barbara, the only stations underlain by sediments.

Uncorrected times of the strong second arrivals on these records fit closely to the equation $t = 5.1 + \Delta/7.0$ and might be considered to represent the refracted wave P_m. Amplitudes are much higher than would be expected for this wave (Gutenberg, oral communication). A trial fit to a computed curve for a reflection from the same horizon as the second reflection on the Monolith normal incidence record shows that the events fit the reflection curve with residuals no larger than for the refraction line. Events similar to these have been reported by TATEL, ADAMS, and TUVE [1953] from work in Maryland, Minnesota, and Tennessee. Using calibrated instruments at many points for repeated shots near Patuxent, Maryland, they demonstrated that the amplitude variations were those to be expected of a reflected wave. In the present case sufficient calibration data were not obtained.

Such a set of strong second arrivals has not been obtained from Corona and Colton blasts, principally because of the lack of stations in the proper range of distance. Three stations in this distance range operated by the Carnegie Institution of Washington for the 1949 Corona blast did not show such arrivals, according to TATEL, ADAMS, and TUVE [1953]. These records have not been available for examination. Three other stations that recorded the 1949 blast, La Jolla, El Cajon, and Point Loma, show weak second arrivals.

Travel times for the strong second arrivals from the Monolith blasts are listed in Table 2; the times are corrected for the limestone hill at the source but not for station elevations. If it is assumed that these arrivals correspond to the strong later reflection on the normal incidence records, a computation of reflector depth and average crustal velocity of a single-layer crust may be made using the formulas

$$V^2 = \Delta^2/(t^2 - t_o^2)$$

$$H = Vt_o/2$$

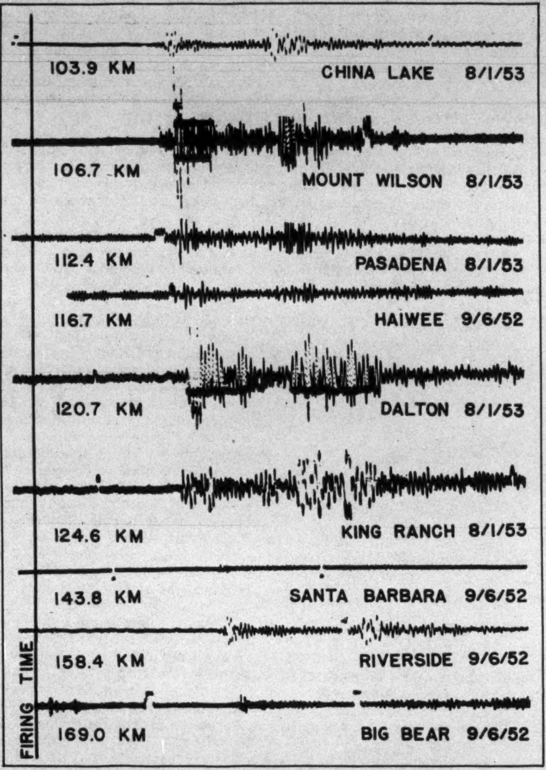

Fig. 4--Records from Monolith blasts of September 6, 1952, and August 1, 1953, at stations beyond critical distance

These computations give a velocity of 6.20 km/sec for the crust and a depth of 31.9 km below sea level for the Mohorovicic discontinuity.

These arrivals might be considered to correspond instead to the reflection near nine seconds on the normal incidence record. In this case a similar computation gives an average velocity of 5.99 km/sec and depth of 26 km below sea level for this reflecting horizon. If the second normal reflection is from the Mohorovicic discontinuity, the first would be from the upper surface of the layer with velocity seven km/sec (the 'basaltic' layer), referred to by REICH [1953b] as the Conrad discontinuity. Taking the difference of travel time of the two normal reflections at Monolith and this velocity, one finds that the layer is 5.5 km thick; the Corona data give a thickness of six km. This again gives a depth to the Mohorovicic discontinuity of 31.5 to 32 km below sea level. If a layer six km thick with a velocity of seven km/sec exists above the Mohorovicic discontinuity, the travel-time curves for the reflections from the Mohorovicic and Conrad discontinuities are only half a second apart over the range in which these strong arrivals have been observed. Possibly the variation in the strength of these arrivals comes from reinforcement and cancellation of the two reflections.

Table 2--Beyond-critical reflections from Monolith blasts

Station	Date	Δ	t	V
		km	sec	
China Lake	August 1, 1953	103.9	19.5	6.35
	September 6, 1952	103.9	19.5	6.35
Mount Wilson	August 1, 1953	106.7	20.4	6.12
	September 6, 1952	106.7	20.5	6.08
Pasadena	August 1, 1953	112.4	21.0	6.21
	September 6, 1952	112.4	21.0	6.21
Haiwee	August 1, 1953	116.7	21.7	6.16
	September 6, 1952	116.7	21.7	6.16
Dalton	August 1, 1953	120.7	22.2	6.18
	September 6, 1952	120.7	22.2	6.18
Riverside	September 6, 1952	158.4	27.6	6.22
Big Bear	August 1, 1953	169.0	29.2	6.21
	September 6, 1952	169.0	29.4	6.16
Average value of V				6.20

Note: H = 31.9 km below sea level.

More elaborate computations may be made using available velocity data from other sources. First arrivals from Monolith blasts out to 70 km agree with results obtained by GUTENBERG [1951a] from Corona and Colton blasts for a velocity of 5.9 km/sec. Beyond 70 km the Monolith first arrivals are too weak to be trusted. Corona blast data presented by GUTENBERG [1951a; 1952] and ROONEY, TATEL, and TUVE [1950] show the presence of a second layer with velocity 6.5 to 6.8 km/sec. On the other hand, earthquake studies by RICHTER [1950] give an average velocity of 6.34 km/sec for the first 16 km of the crust, and a restudy of his original data in terms of multiple layers shows that they will not fit for any velocity much over 6.5 km/sec in the second layer. Velocities in this region in the material below this second layer are not known from blast refraction data. GUTENBERG [1951b] has found evidence for a zone of lower velocity from earthquake amplitudes. There is evidence from earthquakes that there is a layer with velocity seven km/sec at the base of the crust. These data are summarized in Table 3. Introducing these into the solution for the crustal thickness, one finds that there are more unknowns than equations. The thickness of the layer with velocity 6.34 to 6.8 km/sec and of the low-velocity zone cannot be determined separately, but the sum of their thicknesses and the highest possible velocity in the low-velocity zone can be obtained.

Table 3--Crustal velocity information derived from earthquake and blast refraction data

Thickness	Velocity
km	km/sec
0.5 to 1.5	Low
5.5 to 8	5.9
Unknown	6.34 to 6.8
Unknown	Low
About 6	7
....	8.2

Four models fitting the range of velocities shown in Table 3 have been introduced into the solution for depth to the Mohorovicic discontinuity. All four models give values between 31 and 33 km below sea level. The maximum velocity in the 'unknown layer' in all cases lies between 5.5 and 6.2 km/sec.

Conclusions--The existence of normal reflections from the Mohorovicic discontinuity shows that the discontinuity is sharp in comparison with the wave length of the reflections. Evidence for the existence of the Conrad discontinuity is strengthened by the presence of the reflection at nine seconds. Computations using all velocity data available give a depth of 32 km below sea level for the Mohorovicic discontinuity in the vicinity of the Corona and Monolith quarries and also indicate that a low-velocity channel must exist in the Southern California region.

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ANALYSIS OF STRESS CONDITIONS IN THE UPPER SPRABERRY IN WESTERN TEXAS

William B. Farrington

Abstract--Upper Spraberry cores were studied to learn whether fractures were open in the formation or only incipient. Release of fluid pressures in a pressure vessel into which core samples had been placed produced longitudinal axial fractures in previously unfractured cores, showing that some of the fractures must be incipient. A statistical study showed that the core diameters across fractures were slightly less than along fractures. The difference in core diameters may have been the result of a small difference in the magnitude of the two principal horizontal stresses, which difference was computed from a knowledge of Young's modulus under formation conditions. The Mohr diagram was used to analyze the stresses in three dimensions, while the Mohr envelope indicating rupture conditions was constructed with data obtained from tension and compression tests on core samples. The tensile stress required to cause fracture under formation conditions as determined with the Mohr diagram compares favorably with the Hydrafrac pressure required for the 'formation break.' The average horizontal stress appears to be about half the vertical stress due to overburden, and this may be due in part to the low Poisson ratio of the rock.

Introduction--Production of oil from the Spraberry formation in the Southern Midland Basin depends on close-spaced fractures or incipient fractures in the formation. The permeability of this siltstone is so low that little oil would be produced if either natural or artificially developed latent fractures did not provide channels along which oil could flow to the wells. This study was undertaken to learn something of the nature of these fractures and of the forces to be overcome in opening the fractures. Cores from the Upper Spraberry from several wells in the North Pembrook field were studied. These cores were typical of other Spraberry cores in that about half had smooth fractures lengthwise down the center, while a very few had more than the single fracture. Measurements showed that 78 pct of the central fractures were within 0.10 inch of the center of the 3.5-inch cores.

It is possible that open fractures could control the core bit and thus cause cores to be centered on a pre-existing fracture, but Spraberry cores usually appear clean, unmineralized, and thus of recent origin. The presence of some mineralized fractures and fractures containing hydrocarbon residue indicates that some fractures were developed in the formation, but the majority of those seen in the cores do not appear to have been open. The problem then is to learn what forces act during the coring process to cause the appearance of the clean breaks near the centers of the cores.

Pressure vessel experiments--In order to learn whether the release of pore pressure could produce fractures in unfractured Spraberry cores, the cores were repressurized in a pressure vessel followed by sudden release of pressure. The vessel constructed for the purpose was large enough so that several short pieces of core could be tested simultaneously using fluid pressures up to 5000 psi. Water did not satisfactorily penetrate the pore spaces of the core, probably because of swelling of clays and because of residual hydrocarbons present. Acetone was not successful because it caused leaks at the gaskets of the pressure vessel, and kerosene became the final choice. Since many of the cores tested had permeabilities of only a few microdarcys, the samples were left under pressure for at least 24 hours before release of pressure. Even this length of time may have been insufficient for the voids near the center of the core to reach the pressure of the kerosene surrounding the core.

The sudden release of pressure caused the kerosene to start flowing out of the core. The pressure near the outside of the core would thus drop to zero rather quickly while that near the center would remain longer near the pressure which had been applied. The solid granular structure would thus be under a tension which would be a maximum at the center of the core and would drop off radially in all directions to zero near the edge. This tension could cause the development of fractures along planes of weakness, and the tendency to fracture would be a maximum at the center.

By this method a number of fractures were produced down the centers of previously unfractured cores. Many cores separated along bedding planes, and many showed no change at all. In some cases there appeared partial fractures which did not actually separate the core into two halves. Thus the release of oil pressure during coring may have been the cause of fractures in Spraberry cores. Whether or not this is true, the production of a few smooth axial fractures in the pressure vessel does show that there are at least some latent or incipient fractures present in the formation. The closeness of the fractures to the cores' axes indicates that these planes of weakness are closely spaced in the formation, and the one nearest the core center should have the greatest tendency to open.

One thin section happened to be made across the end of a core where a partial fracture later developed. No sign of any latent fracture or lineation could be seen in this thin section.

Apparent fracture widths--Even though the evidence presented above shows that some fractures appearing in the cores were not present before coring, it was decided to measure accurately core diameters to learn whether there was any evidence that some of the fractures were open in the formation. If a fracture with measurable opening existed in the formation and were included in the center of a round core, the core as measured at the surface with the two sides of the fracture in contact would have a shorter diameter perpendicular to the fracture than along it. Measurements were made on 83 core samples with single fractures, and the diameter perpendicular to the fracture was subtracted from the diameter along the fracture to give the fracture width in each case. Lack of roundness of the cores caused scattering of the readings.

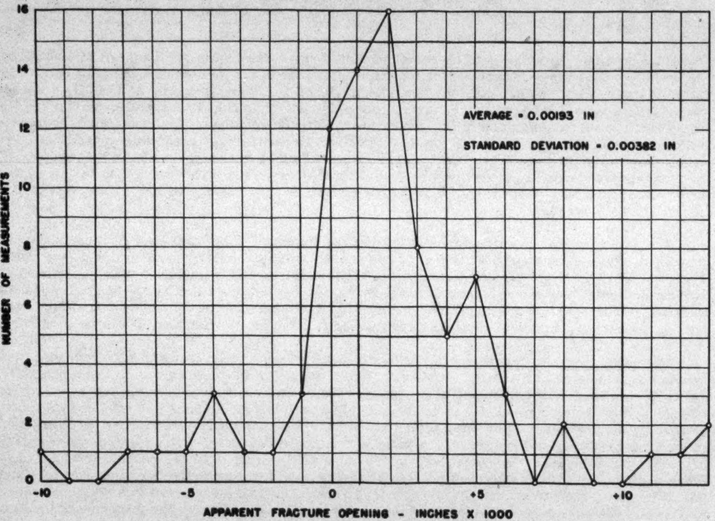

Fig. 1--Distribution of 83 measurements of apparent fracture opening obtained by subtracting the diameter of each core perpendicular to the fracture from the diameter parallel to the fracture

The results of these measurements as shown in Figure 1 seem to indicate a fracture opening averaging about 0.002 inch in the formation. However, the presence of latent fractures in the formation as demonstrated by the pressure-vessel experiments and the cleanness of the fractures measured leads to another explanation than that they were open in the formation. If the rock had been under a differential horizontal stress before it was cored, the originally round core would rebound to an elliptical cross section after release of stress as shown in Figure 2. From a

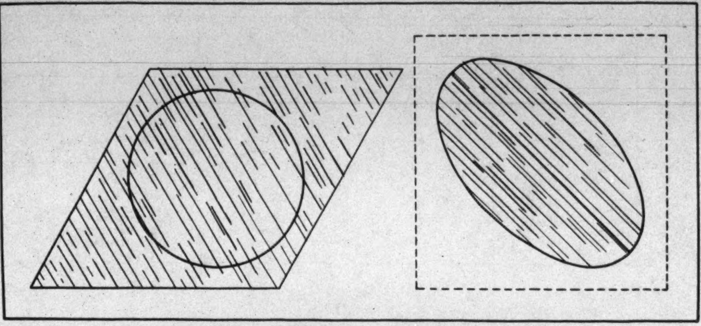

Fig. 2--Effect of a differential horizontal stress in producing core ellipticity and an apparent fracture opening even though fracture may not have been present in the formation

knowledge of Young's modulus, E, Poisson's ratio, and the average core deformation found above, the magnitude of the differential stress can be computed. Tests were made to learn the physical constants of the rock under various loads. The magnitude of the horizontal stress perpendicular to the fracture direction as obtained from the injection pressures at the bottoms of wells during Hydrafrac [CHRISTIE and BLACKWOOD, 1952] and Strata-frac [MOORE and McCORMICK, 1951] completions is about 2700 psi. At this stress E is 1.7×10^6 psi, and Poisson's ratio is 0.048, requiring a difference of 896 psi in the two horizontal stresses to cause the deformation of 0.00193 inch in 3.5-inch cores.

The Mohr diagram--BUCHER [1921] and GOGUEL [1948] have used the Mohr diagram to study stresses in rocks under rupture conditions. Figure 3 is a Mohr diagram drawn to show Spraberry conditions. Normal stresses on any plane are plotted as abscissas, and shearing stresses are plotted as ordinates. At any point in a body under stress there are always three mutually perpendicular planes on which there is only direct stress (pure tension or compression) and no shear, and these are known as principal planes. The combination of shear and direct stress on any plane perpendicular to the intermediate principal plane will lie on a circle of diameter defined by the major and minor principal stresses. This combination can be found from the intersection of the circle and a line through the minor principal stress making the same angle with the x-axis as the plane in question does with the major principal plane. Stresses on planes perpendicular to the major and minor principal planes likewise lie on circles represented, respectively, by the small and intermediate circles of Figure 3. The shaded area represents the only possible combinations of shear and compressive stress existing under present formation conditions for any plane at any orientation. The straight lines on the diagram form the Mohr envelope which is dependent on the properties of the rock. When stresses increase to the point where the Mohr circle touches the envelope, shear failure or rupture occurs along a plane whose orientation can be determined by a line drawn through the minor principal stress to one of the points of tangency of the circle and envelope.

The Mohr envelope was constructed from tension and compression tests carried to failure under direct uniaxial stresses, Mohr circles for which are shown dotted on Figure 3. With stresses applied parallel to bedding, failure in tension averaged 1780 psi, while failure under compression averaged 9380 psi. In the formation the major principal stress, caused by overburden, is about 7000 psi and acts vertically. The minor principal stress is 2700 psi as determined above and acts normal to the fracture or latent fracture planes. The intermediate principal stress is 2700 psi plus 896 psi, or 3596 psi, and acts horizontally parallel to the fractures.

The Mohr diagram as shown in Figure 3 and as outlined in the last paragraph can now be used to find the principal stresses at rupture both in the formation and in the pressure vessel. To develop a latent fracture under reservoir conditions requires a net tension of about 500 psi (larger dashed circle), which means that a tension of 3200 psi must be applied to the acting compression of 2700 psi across the fractures. Once the fracture has been started the gel pressure would have

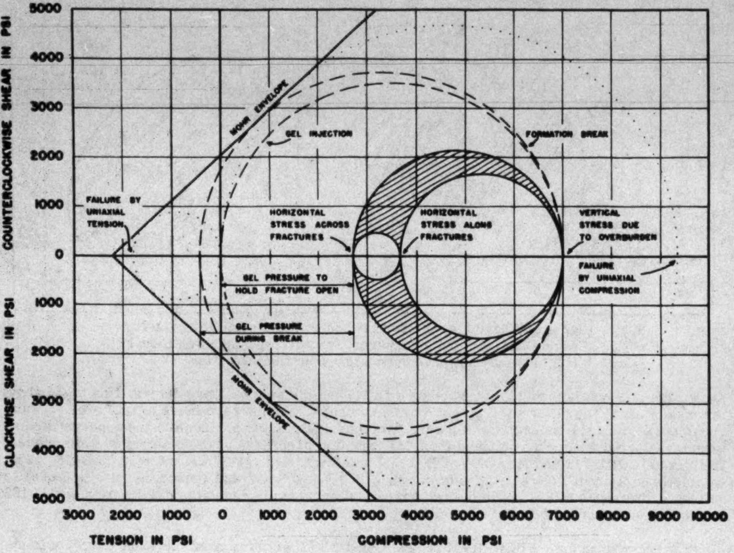

Fig. 3--The Mohr diagram

to overcome only the 2700-psi compression across the fracture (smaller dashed circle). Further extension of the fracture would not require much pressure in excess of that required to merely hold the fracture open because there would be a stress concentration at the end of the existing portion of the fracture, and the fracture would extend quite easily just as a split in wood can be easily extended. This is confirmed by the fact that pressures developed at the bottom of the hole during gel completions often reach a peak pressure soon after the start of the treatment which is called the 'formation break.' It can be demonstrated that the tensile stresses developed in the formation next to the well are the same as the hydrostatic pressure of the gel acting against the walls of the well bore. After this peak the pressures decrease about 600 psi to fairly constant injection pressures of about 2700 psi [MOORE and McCORMICK, 1951]. This injection pressure would thus be just enough to hold the fracture open, plus a small excess to overcome the friction of gel flowing into the fracture. The pressure required to open the fracture to a considerable width should be only a small increment more since the adjustment within the rock could take place throughout a large distance perpendicular to the plane of the fracture.

For each formation stress considered above and shown on Figure 3, it is considered that the total stress acts through the solid rock structure. All principal stresses should be decreased by an amount equal to any oil pressure acting. Any change in the proportion of the total stress represented by oil pressure would not change the gel pressure during injection since the gel would act against the same total of stress plus oil pressure. However, variation of oil pressure would slightly change the gel pressure required for the break. The Mohr circles indicating present stress conditions would all be shifted toward the origin by an amount equal to the oil pressure. Thus if the oil pressure were 2000 psi, the major principal stress in the solid rock structure would be 2000 psi less, or 5000 psi; and the intermediate and minor principal stresses in the solid structure would also be decreased 2000 psi to 1596 and 700 psi, respectively. If a circle were drawn through the 5000-psi point tangent to the Mohr envelope, it would intersect the abscissa at a tension of 840 psi. This indicates that the gel pressure during the break would have to be 3540 psi (840 + 700 + 2000) instead of the 3200 psi needed for the break when there is no oil pressure in the formation. The small variation of only 340 psi shows that gel pressure cannot be used as an indicator of effective oil pressure near the well bore during the break.

Upon release of pressure in the pressure vessel the rock structure is subjected to an intergranular tension which is equal in all directions, thus reducing the Mohr circle to a point. This means that the intergranular tension must be about 2200 psi to produce rupture rather than the 1780 psi required for the tension tests with stress applied to only one axis. The reservoir pressure in this field was originally about 2400 psi but soon dropped considerably.

The fact that the horizontal stresses are only about half the vertical compressive stress due to overburden may be explained by the low value of Poisson's ratio, assuming that the formation reached its present elastic properties before much of the overburden was deposited. The value of Poisson's ratio for the Spraberry samples tested was found to increase with an increase of compressive stress to 0.072 at 7000 psi.

Conclusions--Some of the fractures occurring as longitudinal breaks down the axes of Spraberry cores are latent fractures or planes of weakness which are closely spaced in the formation. They are developed in the cores by tension produced by the release of the oil pressure. The horizontal stress in the formation acting across the latent fractures is somewhat less than that acting along the fractures, but both horizontal stresses are considerably less than the vertical stress due to overburden.

Acknowledgment--This paper is a condensation of a portion of a thesis submitted by the author to the Department of Geology and Geophysics at the Massachusetts Institute of Technology in partial fulfillment of the requirements for the degree of Doctor of Philosophy. The assistance of W. L. Whitehead, who supervised the thesis, is gratefully acknowledged.

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A GRAVITY SURVEY OF THE RIO GRANDE TROUGH NEAR SOCORRO, NEW MEXICO

Richard C. Anderson

Abstract--A gravity survey involving 61 stations was made across the Rio Grande trough near Socorro, New Mexico. The anomaly observed was such that a two-dimensional type of analysis could be used to determine the form of the trough in this area. Separate analyses of the data were made for each of two assumptions: (1) that the Tertiary fill was composed principally of unconsolidated sediments, and (2) that the Tertiary fill was made up primarily of consolidated sediments and volcanics. The analyses yielded limiting values of 2100 and 5800 ft, respectively, for the greatest thickness of Tertiary fill.

Introduction--The general geology on the flanks of the Rio Grande Valley near Socorro, New Mexico, has been studied by WILPOLT and WANEK [1951], WALDRON [1953], and DARTON [1928]. Figure 1 shows a generalized map of the surface outcrops. Little or no subsurface information is available in this area. Consequently, a gravity survey was performed during the fall of 1952 and the spring of 1953 in order to provide some substantial basis for a postulation of the subsurface structure of the valley.

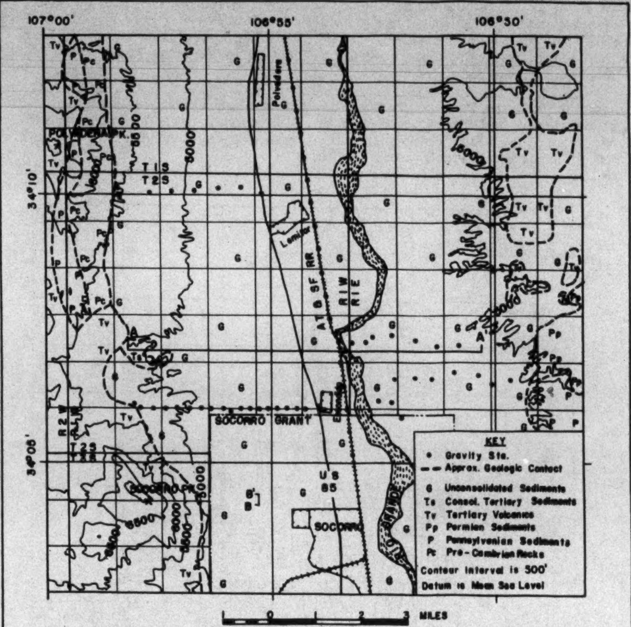
Geology and density relations--The known surface geologic evidence indicates that the Rio Grande trough in this region is a large graben structure, highly faulted along the edges. It is composed of Precambrian and Paleozoic rocks partly filled in with Tertiary volcanics and arid lake sediments, but primarily filled in with Tertiary gravels and some Quaternary alluvium in the arroyos and Rio Grande channel.

Table 1--Tabulation of density samples of consolidated rocks

Geologic age	Rock type	Number of samples	Density			
			Minimum	Maximum	Average	
			gm/cc	gm/cc	gm/cc	
Tertiary	Vesicular basalt	4	2.30	2.55	2.46	a
	Rhyolite	2	2.38	2.47	2.43	
	Tuff	3	2.05	2.34	2.15	
	Siltstone	3	2.35	2.42	2.39	
	Conglomerate	1	...	...	2.42	
	Sandstone	1	...	...	2.04	
Permian	San Andres limestone	4	2.53	2.71	2.60	b
	Yeso formation	4	2.51	2.56	2.54	
	Abo formation	4	2.63	2.70	2.66	
Pennsylvanian	Limestone	4	2.69	2.70	2.70[c]	
Precambrian		5	2.48	3.05	...[d]	

[a] Weighted average 2.4 gm/cc.
[b] Arithmetic average 2.6 gm/cc.
[c] Arithmetic average 2.7 gm/cc.
[d] Weighted average 2.7 gm/cc.

An analysis of density samples taken from the rock outcrops along the flanks of the valley is shown in Table 1. The weighted average densities, where used, reflect an estimate of the proportionate composition of each sample type in the exposed rocks of the area. The density values for Pennsylvanian and Permian rocks fall in a quite narrow range, and the average values are considered accurate to ±0.05 gm/cc. The values for the Precambrian rocks are not nearly so consistent,


107°00'
106°55'
106°50'
34°10'
34°05'
POLVADERA PK.
T 1 S
T 2 S
R 2 W
R 1 W
R 1 W
R 1 E
Polvadera
Lemitar
AT & SF RR
SOCORRO GRANT
Escondida
US 85
SOCORRO
SOCORRO PK.
RIO GRANDE
B'
B
A
A'
5500
6000
6500
5000
G
Ts
Tv
Pp
P
Pc
KEY
• Gravity Sta.
— — Approx. Geologic Contact
G Unconsolidated Sediments
Ts Consol. Tertiary Sediments
Tv Tertiary Volcanics
Pp Permian Sediments
P Pennsylvanian Sediments
Pc Pre-Cambrian Rocks
Conteur interval is 500'
Datum is Mean Sea Level
0 1 2 3 MILES

Base map is USGS Socorro Quadrangle Sheet
Edition of Sept. 1906

Geology east of the Rio Grande is from USGS "Oil and Gas Investigations Map OM 121" entitled, "Geology of the Region From Socorro and San Antonio East to Chupadera Mesa, Socorro County, New Mexico" by R.H. Wilpolt and A.A. Wanek

Geology west of the Rio Grande is from an unpublished thesis by John F. Waldron and from field observation.

Fig. 1--Map of the Socorro quadrangle showing geologic contacts and locations of gravity stations

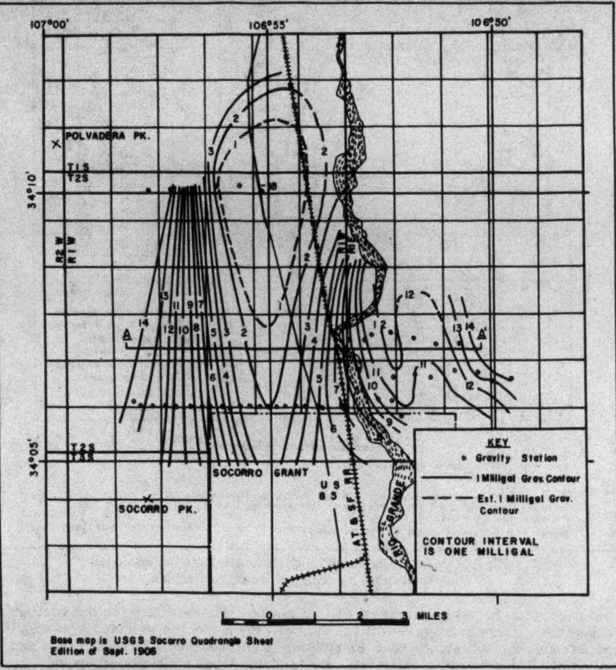
but the average value probably is correct to ±0.1 gm/cc. The densities for the Tertiary consolidated rocks show a large average deviation, and the accuracy of the weighted averages is extremely uncertain, because the subsurface rock distribution is unknown and also because the densities of the actual samples, the basalt in particular, are far from those normally accepted.

A density profile [NETTLETON, 1940] was made across an arroyo in the area of Tertiary gravels along Section BB' (Fig. 1). The most probable density calculated from this profile was 2.2 ± 0.1 gm/cc.

Survey procedure--All gravity readings were made with a Worden gravimeter (no. 111 - NMIMT). The scale constant is 0.0876 mgal/scale division and a vernier permits readings to 0.1 scale division.

Aerial photographs were used to locate the gravity stations. The locations then were transferred to the U. S. Geological Survey Socorro Quadrangle Sheet with an estimated precision of ±100 ft. The elevation survey was made with transit and stadia rod and tied to U. S. Coast and Geodetic Survey bench marks. Elevation error at any station probably does not exceed ±0.5 ft. The instrument drift was very regular, and checks were made by returning to the base station at least once every 70 min during the course of the survey. Drift, latitude, terrain, and elevation corrections were applied to all readings to obtain corrected Bouguer gravity values. Terrain corrections were made using HAMMER's [1939] charts and tables. For stations in very rough terrain, individual topographic maps covering a 200-ft radius from the station were made in order to calculate accurate terrain corrections.

A map of the relative Bouguer gravity in the surveyed area is shown in Figure 2. The striking feature of the anomaly is its very pronounced two-dimensional character which permits analysis with standard two-dimensional charts. No attempt was made to correct for a regional gradient on the map, since insufficient data are available.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POLVADERA PK.
T1S
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R2W
R1W
T2S
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SOCORRO PK.
SOCORRO
GRANT
US 85
AT & SF RR
RIO GRANDE
A
A'
KEY
Gravity Station
1 Milligal Grav. Contour
Est. 1 Milligal Grav. Contour
CONTOUR INTERVAL IS ONE MILLIGAL
0 1 2 3 MILES

Base map is USGS Socorro Quadrangle Sheet Edition of Sept. 1906

Fig. 2--Relative Bouguer gravity map of the Rio Grande Valley near Socorro

Analysis of data--Figure 3a shows the relative gravity anomaly along section AA' (Fig. 1 and 2). Two hypothetical mass distributions which might cause the anomaly were computed in order to show minimum and maximum values of the pre-Tertiary relief. The assumptions for the minimum section (Fig. 3b) are that the anomaly is produced by a valley in the Pennsylvanian-Permian section (thinly covered in places by Tertiary volcanics) of effective density 2.7 gm/cc and filled, primarily, with unconsolidated sediments of effective density 2.1 gm/cc. In this case, Tertiary volcanics and consolidated sediments are presumed to account for a negligible part of the valley fill. Computations based upon these assumptions gave a fill of 2100 ft in the deepest part of the trough.

The assumptions for the maximum section (Fig. 3c) are that the anomaly is produced by a valley in the Pennsylvanian-Permian section of effective density 2.7 gm/cc and filled with Tertiary

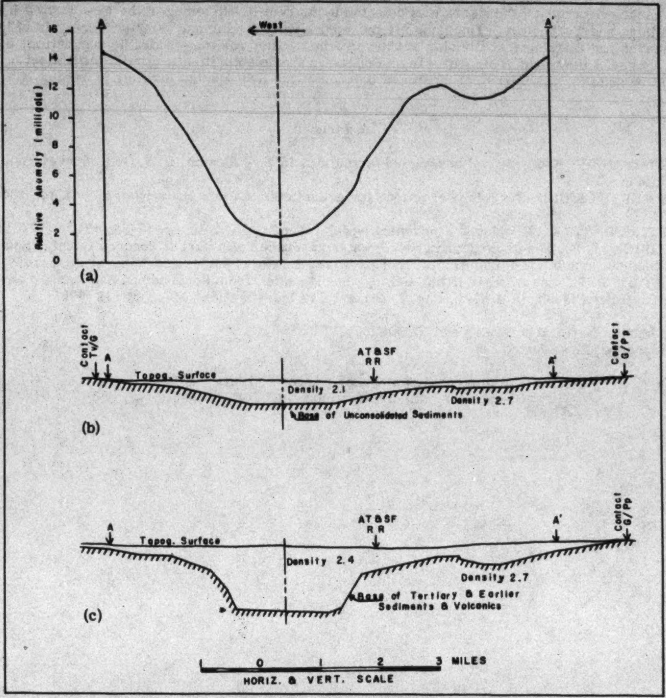

Fig. 3--Relative gravity and computed geologic sections along AA′: (a) relative gravity along AA′; (b) postulated valley section of minimum pre-Tertiary relief; and (c) postulated valley section of maximum pre-Tertiary relief

and earlier sediments and volcanics of effective density 2.4 gm/cc. In this case, Tertiary volcanics and consolidated sediments are presumed to account for a large portion of the valley fill. The greatest computed depth to pre-Tertiary rocks is 5800 ft.

In fixing the valley sections shown, a two-dimensional elliptical valley was determined which would produce an anomaly approximating that observed along a plane through its major axis. This ellipse then was modified by trial and error (using a two-dimensional chart) until a satisfactory correspondence (±0.3 mgal) was achieved between the computed and the observed anomaly curves. Finally the reference plane was formed to the shape of the topography along AA′ with the consequent warping of the computed valley section.

Conclusion--The assumptions made in determining the maximum and minimum sections of Figure 3 are much simpler than the actual conditions. They represent, however, the probable extreme conditions and, along with the Bouguer gravity map, afford limits and provide a basis for a more accurate postulation of the subsurface valley structure than heretofore has been possible. Any future geologic speculation on the structure of the valley, however different from the limiting assumptions, must necessarily be consistent with the gravity picture.

Acknowledgment--This work was directed by Marvin H. Wilkening of the New Mexico Institute of Mining and Technology. The author is indebted further to Hartmut Winkler, formerly of the Research and Development Division of the same institution, for many valuable suggestions during the course of the work. This paper forms part of a thesis submitted in partial fulfillment of the requirements for the Degree of Master of Science at the New Mexico Institute of Mining and Technology.

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REPORT OF THE COMMITTEE ON SNOW, 1953-1954

R. A. Work, Chairman

M. E. Baudendistel
Walter U. Garstka
Eric Hinton
Clyde E. Houston
Gordon J. H. Kidd
J. C. Marr
C. C. McDonald
Vincent J. Schaefer
Walter T. Wilson

The following report has been prepared by the Committee from a questionnaire sent to individuals and agencies active in snow research.

M. E. Baudendistel (U. S. Forest Service, Portland, Oregon)--Studies will soon be initiated on the H. J. Andrews Experimental Forest to determine differences in runoff from snow melt from areas logged wholly or in part as compared with uncut areas.

George W. Craddock (Chief, Division Watershed Research, U. S. Forest Service, Ogden, Utah)--Studies of snow blowing and drifting from adjoining experimental watersheds are planned in order to reveal some variations of runoff which cannot logically be attributed to differences in the amount of snow that falls directly on the catchment areas.

W. T. Frost (Oregon Snow Survey Leader, U. S. Soil Conservation Service, Portland, Oregon)--A network of aerial snow-course markers to be photographed from the air has been established in Oregon. Density factors from nearby snow courses will be applied to depths photographed from the aerial markers. Results will be compared with those of regular snow-course measurements.

Several electrical fiberglass soil-moisture measuring units are to be established in selected watersheds of Oregon. Measurements will be made and studied in cooperation with Oregon State College Agricultural Experiment Station to assess water contributions from the winter snow pack necessary to bring watershed soils up to field capacity in the spring.

Walter Garstka (U. S. Bureau of Reclamation, Denver, Colorado)--The experimental studies of ice pressure by the Bureau of Reclamation were discontinued in 1951. The more important results of both field and laboratory investigations were summarized in a paper, Ice Pressure Against Dams, Experimental Investigation by the Bureau of Reclamation, by G. E. Monfore [Proc. Amer. Soc. Civ. Eng., v. 78, Sep. no. 162, December, 1952]. Essentially the same data are contained in Bureau of Reclamation Laboratory Report no. C-662.1A, Ice Pressure Measurements, December 7, 1953. The latter report includes an annotated bibliography of 22 references on the subject of ice pressure.

The active data-gathering phase of the Bureau of Reclamation-Forest Service Cooperative Snow Investigations terminated with the 1950 snow-melt season. Analyses of that season were presented in Report no. 3, 1950 Snow-Melt Season, Progress in Snow-Melt Investigations at the Fraser Experimental Forest, Colorado, released by the Bureau of Reclamation and Forest Service. All analyses for this cooperative effort have been completed and a final report is being assembled.

R. W. Gerdel (Snow, Ice, and Permafrost Research Establishment, Wilmette, Illinois)--We have been studying the settling and deformation of snow profiles with a unique slide-wire device, originally developed in Switzerland. It is giving us some interesting information on the self-compaction, melting, and possible upward sublimation of snow layers without disturbing the snow. This device may solve the problem of snow melt and soil priming during the winter. Effectively we have one leg of a Wheatstone bridge permanently installed in the snow and read the change in thickness of a layer as a change in resistance of the wire.

W. A. Lang (Chief Hydrographer, Southern California Edison Co., Los Angeles, California)--A network of 12 snow-survey aerial markers has been installed in the San Joaquin River Basin and Sierra Nevada Mountains. These aerial snow markers are to be photographed from the air at monthly intervals from December to July.

John W. Marr (Director, Institute of Arctic and Alpine Research, University of Colorado, Boulder, Colorado)--The Institute, in its long-range study of the ecology of the East Slope of the Front Range, is making measurements of snow depth and water content. Total precipitation and soil moisture are recorded also in order to determine 'all' aspects of environment water each month. Evaporation measurements are to be added as soon as possible.

Information on the interrelations between plant species, plant communities, and snow accumulation are being collected. This includes observations of the effect of snow accumulation on the reforestation of areas in the Sub-Alpine Forest and the distribution of types of tundra plant communities in the Alpine tundra.

The results are being used to interpret vegetation features in the Sub-Arctic Forest-Arctic Tundra Transition Area in Quebec (or Ungava). Investigations are being conducted attempting to work out the particular role for which snow accumulation is responsible in altering the environment on different exposures in the Montane Forest.

C. C. McDonald (Staff Engineer, U. S. Geological Survey, Tacoma, Washington)--In the field of forecasting seasonal runoff from snow-survey data, joint studies of the Soil Conservation Service, Geological Survey, and Oregon State College have indicated the adaptability of antecedent base flow of the stream to the improvement of the relationship between water content of the snow and runoff [Nelson, McDonald, and Barton, Western Snow Conf., April, 1953].

Milton S. Sachs (Chief, Water Utilization Section, Bonneville Power Administration, Portland, Oregon)--In the interest of effective utilization of water for electric energy production, the Bonneville Power Administration has entered into a hydrologic cooperative research program with the University of Washington. A report by D. R. Makela, Short-Term Stream Flow Prediction from Snow Melt, Middle Fork Flathead River, has been submitted by the University of Washington. Copies may be received from the Bonneville Power Administration.

C. C. Warnick (Associate Research Professor, Engineering Experiment Station, University of Idaho, Moscow, Idaho)--Work during the past year involved testing precipitation gages of different diameters in the wind tunnel under artificial snowstorms, using sawdust that had terminal velocities the same as two different types of snow crystals. Additional development work was carried forward on the Shasta windshield for the Bureau of Reclamation's new radio-reporting rain and snow gage. Improved performance was obtained both with the wind tunnel gages and the experimental field gages.

The Forest and Wildlife Experiment Station at the University of Idaho is studying snow depth as it influences the availability of forage for deer and elk. A series of measurements of snow depth are being correlated with feeding habits of big game animals.

Walter T. Wilson (Acting Chief, Cooperative Studies Section, reporting for Max A. Kohler, U. S. Weather Bureau, Washington, D. C.)--Recent investigations by the Weather Bureau in its program of water-supply forecasting have disclosed instances where forecasts can be improved by including snow-pack water equivalent as one of the variables along with seasonal precipitation.

A recent study has indicated that much of the variation in seasonal precipitation catch and accumulated snow pack from station to station in rugged terrain is related to the amount of natural shelter at each site of observation, and that average wind speed is a good measure of the degree of shelter. A completed analysis of the midwest April, 1952, flood is to be published as Weather Bureau Technical Paper no. 23.

Lorne W. Gold (Snow and Ice Section, reporting for R. F. Legget, Director, Division of Building Research, National Research Council, Ottawa 2, Ontario, Canada)--A cold laboratory for this Section will be completed and in use by summer of 1954. A program of research on snow and ice, which we have looked forward to for some time, will then be initiated. The initial work on this program will place emphasis on the behavior of snow and ice under applied loads.

The Snow Survey of Canada, which began in 1947, has continued with at least ten observation stations each year. Technical Memorandum no. 21 describes the preliminary results of this project to 1950.

Morlan W. Nelson (Snow-Survey Leader for Columbia Basin, U. S. Soil Conservation Service, Boise, Idaho)--Two additional forecasting variables, which have proven reliable in forecasting seasonal runoff from snow melt, have been incorporated into forecast procedures. A soil-priming variable has been used as an estimate of soil-moisture status over any particular watershed. Secondly, base flow of a river as measured near the first of November has also been used successfully as an indication of soil-moisture status on a watershed. Papers published on these procedures are: Soil Priming in Relation to Snow Surveys and Flood Regulation by Nelson, Wilm, and Work [Trans. Amer. Geophys. Union, v. 34, pp. 240-248, 1953]; Base Flow as the Parameter in Forecasting April through June Runoff by Nelson, McDonald, and Barton [Trans. Western Snow Conf., April, 1953]. Preliminary work has been completed on the use of a consumptive-use factor for increasing the accuracy of forecasts of flow from melting snow. This material has not been completed at this time.

David M. Rockwood (Technical Director, Snow Investigations, U. S. Corps of Engineers, Portland, Oregon)--In 1953-1954 the Snow Investigations Unit, Corps of Engineers, has concentrated on analysis of data collected during the operation of three snow laboratory basins (Central Sierra, Upper Columbia, and Willamette Basin). The Central Sierra Snow Laboratory remained in limited operation during the 1953-1954 snow season to obtain more data from two snow lysimeters together with related special observations during the melt season. The Snow Investigations Unit was transferred to North Pacific Division, Portland, in June, 1953, and has a staff of ten.

Heat transfer to the snow continued to be the principal subject of analysis. Two studies of radiation and heat exchanged in late-season snow patches in heavy forest were based on observations of short-wave and long-wave radiation and melt at Willamette Basin Snow Laboratory in July, 1952. Based on observations of a melting snow patch in dense forest during clear, calm weather, a melt formula is developed with heat components expressed in terms of air temperature, absolute humidity, and short-wave radiation. For the conditions described, about one-half the melt is due to long-wave radiation (Research Notes 11 and 12).

The thermal-balance approach was also used in two studies based on observations of melt at two snow lysimeters at Central Sierra Snow Laboratory. On the basis of a study of clear-weather snow melt, recommendations were made on the use of the thermal-budget method of estimating snow melt (Research Note 17). Estimates of melt made by thermal-balance and water-balance methods agreed closely with observed amounts of snow melt occurring during a heavy rain on a deep snow pack (Research Note 18). Using Willamette Basin Snow Laboratory data, regression equations were derived for rainless periods in April and May by correlation of daily volumes of snow-melt runoff with air temperature and vapor pressure (Research Note 19). A modified day-degree factor was used in computing melt in a water-balance method of forecasting runoff for a 400-sq mi Cascade drainage basin where meteorological data are scanty (Research Note 21). Ground melt of the bottom of the snow pack was studied, using data from deep-pit and snow-settling meter observations made by the Snow, Ice, and Permafrost Research Establishment at Central Sierra Snow Laboratory during the 1952-1953 snow season (Project CW-171, Tech. Bull. 16). The relation between upper-air flow and thermal balances and snow-melt runoff in the Western United States, May, 1949, and May, 1950, was investigated in an exploratory study. Results show how changes in the circulation of the upper air are reflected in snow-melt runoff (Research Note 15).

Two studies of precipitation distribution and estimated gage deficiency were nearing completion. In a study using yearly precipitation data at Willamette Basin Snow Laboratory, it is suggested that where gage deficiencies and poor areal sampling of the basin give an unsatisfactory basis for estimating mean basin precipitation, a more reliable value of mean basin precipitation may be computed as measured runoff plus estimated losses. The Thornthwaite formula was used to compute the evapotranspiration component of the losses (Research Note 20). Precipitation gage deficiencies were the subject of analysis for Central Sierra Snow Laboratory data. Here the network of paired precipitation gages and snow courses, the frequent snow surveys, and the infrequency of rain on snow permitted a direct comparison of precipitation-gage snowfall catch with accumulated water equivalent at the adjacent snow course (Research Note 22).

In an exploratory study, relations were examined between spring-season snow-melt runoff from the Columbia River at The Dalles and winter runoff for selected coastal streams. In another miscellaneous study, plans were made for a reliable and inexpensive electric analog for rapid computation using standard routing procedures. The report on the radioisotope-radio-telemetering snow gage (Project CW-170) is being completed by personnel of the Hydrology Section of South Pacific Division, Corps of Engineers.

During the past year, the unit issued seven research notes, two technical bulletins, and the hydrometeorological log for Central Sierra Snow Laboratory for 1951-1952. Five more research notes are scheduled for early publication, and a paper summarizing the results of the lysimeter studies was prepared for the Rome meeting of the International Union of Geodesy and Geophysics.

George W. Peak (Snow Survey Leader, U. S. Soil Conservation Service, Casper, Wyoming)--Some work has been done by this office with respect to the methods required to introduce temperatures into a multiple correlation for April 1 stream-flow forecasting.

The April 1 water content of the snow pack represents the algebraic sum of the values of all the climatological factors involved in this accumulation. Prior to the April 1 snow survey, evaporation and transpiration losses are not considered; however, the extent of snow melt in the late winter is highly significant. A correlation involving only April 1 water content, the extent of soil moisture at fall freeze-up, and the influence of spring precipitation produces errors of estimate which, when plotted against February and March temperatures, produce a positive regression curve, indicating temperatures to be proportional to the increase in soil moisture and therefore directly related to the yield from the measured values of the April 1 snow cover.

There is an interval, beginning with the April 1 snow survey and ending with the change from winter flow to the upward surge of the hydrograph, during which time the stream flow does not reflect snow melt. Part of the depletion in the snow cover is the transfer of storage in the snow to storage in the soil plus a very minor contribution to the dependent variable, April-September runoff. During this period, the extent of this 'loss' is the requirement of the remaining soil deficit and this amount is determined by two variables, namely, the soil-moisture index of the preceding fall and the degree of melt prior to the snow survey. There are also real losses from evaporation and transpiration. The regression line, in this second interval, is negative, indicating temperature to be directly proportional to losses in the water content of the snow pack and, therefore, indirectly proportional to the amount of runoff.

The third temperature interval begins at the time of soil saturation and continues as long as the soil maintains storage capacity. The date at which the hydrograph reaches its peak indicates the end of this period. Temperatures during this interval form a positive regression line and are directly proportional to seasonal runoff. High temperatures indicate an earlier and heavier runoff with less loss from seepage, evaporation, and transpiration than that which occurs with comparatively low temperatures, which slow down the runoff and, therefore, increase the losses from seepage and evapotranspiration.

Although temperatures undoubtedly influence the entire runoff, the correlation between temperatures and runoff depreciates when carried beyond the peak of the hydrograph. The snow cover has been depleted and, with this depletion, the water content of the soil recedes; with this recession all climatological factors that influence runoff are proportionately reduced in value.

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(Manuscript received June 11, 1954, and, as revised, September 17, 1954; presented at the Thirty-Fifth Annual Meeting, Washington, D. C., May 3, 1954; open for formal discussion until July 1, 1955.)

Transactions, American Geophysical Union Volume 36, Number 1 February 1955

REPORT OF THE COMMITTEE ON RUNOFF, 1953-1954

W. D. Potter, Chairman

Henry W. Anderson	V. T. Chow	Anthony J. Polos
Ralph W. Baird	E. L. Hendricks	I. C. Pyle
Bertram S. Barnes	Roy E. Oltman	George R. Shanklin

This year the Committee on Runoff had three major objectives: (1) to report on runoff research projects now in progress or proposed for action in the immediate future; (2) to follow up through correspondence on a number of selected papers that have appeared in the Transactions during the past few years; and (3) to solicit discussion of current papers from qualified members.

Under (1), reports have been received listing runoff research projects of the U. S. Forest Service, Geological Survey, Bureau of Reclamation, Corps of Engineers, Bureau of Public Roads, and also projects of the New Jersey Division of Water Policy and Supply and the University of Illinois. These condensed reports have been grouped by subject matter and made a part of this report.

Under (2), letters were sent to TROXELL [1953] and Schwarz [TAYLOR and SCHWARTZ, 1952] asking for progress reports on any additional work that might have been completed on these subjects. The replies to these requests are as follows:

Harold C. Troxell--The phase of our study regarding the influence of ground-water storage on runoff from the mountain areas has been at least temporarily completed. For some months now we have been re-examining the question of natural water loss. This is an extremely important factor in the semiarid and arid regions of Southern California. It is not uncommon in these areas for as much as 95 pct of the precipitation to be disposed of in this manner. We are, therefore, undertaking an analysis of these losses with regard to the physiographic, geologic, and climatic factors. We are working on the theory that frequently the existing meteorological and hydrological data have not been fully used in obtaining the magnitude and area distribution of these losses. If this examination proves to be successful, it may result in a better means of estimating the recoverable water in unmeasured mountain areas with special reference to water-supply problems.

Harry E. Schwarz--The Corps of Engineers project covering a study of unit hydrographs was initiated in December, 1947, as a part of the Civil Works Investigation Program. Upon assignment to the Washington District Office, the study was divided into two parts. Part I was to cover studies of existing methods of unit-hydrograph determinations and development of improved methods for such determinations, especially with regard to synthetic unit graphs. Part II was planned as a compilation of existing unit hydrographs in order to make available to hydrologists unit hydrographs developed all over the country. Both parts of the study were initiated simultaneously. It was decided to concentrate primarily on Part II (unit-hydrograph compilations) to assure greatest immediate benefits to hydrologists. In 1949, three volumes of unit hydrographs were completed containing 263 unit hydrographs at 117 different gaging stations covering areas ranging from 21 to 2950 sq mi. The volumes were distributed by the Office, Chief of Engineers, to offices of the Corps and to the Inter-Agency River Basin Committee. Some of the studies prepared for use in Part I of this project were published in the Transactions [TAYLOR and SCHWARZ, 1952]. A fourth volume of unit-hydrograph compilations has now been completed. This volume contains 106 unit-hydrographs at 29 gaging stations. It is expected that the next studies will cover the use of unit-hydrograph technique on very small and very large drainage areas.

Under (3), lists of names of persons considered qualified to discuss papers dealing with runoff research have been received from various members, and it is the intention of the Committee during the coming year to try to stimulate the discussion of such papers by direct solicitation.

Tabulation of Current Runoff Research

The following tabulation of current runoff research is far from being complete and is presente only as a sample of the type of research that is now being undertaken by various government agencie It supplements a more extensive tabulation by the NATIONAL BUREAU OF STANDARDS [1953].

Watershed runoff studies

U. S. Geological Survey--(1) New York, under supervision of A. W. Harrington: To determine runoff characteristics of small to intermediate drainage areas by operation of short-term (five to ten years) gaging stations. To determine correlation of runoff between the sample areas and adjacent long-term gaged areas. Planned to start last quarter of fiscal year 1954. No specific plans for report.

(2) New York, under supervision of A. W. Harrigton: To determine the most pertinent hydrolog and hydraulic factors affecting runoff for Mohawk River near Schenectady and Glowegee Creeks at West Milton. Active project. Report planned upon completion.

(3) California, under supervision of the Surface Water Branch: To determine the magnitude an duration of base flow for 26 selected streams (previously ungaged) in northwestern California. Started 1951. Probable completion 1956. Report planned. (Similar studies in progress for Georgi Tennessee, Alabama, and North Carolina.)

(4) California, under supervision of the Surface Water Branch: To determine magnitude and frequency of peak discharges for 16 selected streams (previously ungaged) in northwestern California. Started 1951. Probable completion 1958. Report planned.

(5) Nebraska, under supervision of D. D. Lewis: To present an analysis on a regional basis of the magnitude and frequency of floods, based on all available data. Active project. Report planned for 1954. (Similar studies in progress for Georgia, Illinois, Iowa, Mississippi, Alabama, North Carolina, and Arizona.)

(6) Nebraska, under supervision of D. D. Lewis: Analysis of flood magnitude and frequency on 93 small drainage basins, ranging from one to 50 sq mi. Project started in 1950. Probable completion 1956. Report planned. (Similar studies in progress for Maryland, Iowa, Mississippi, Michigan, Alabama, North Carolina, and California.)

U. S. Forest Service--San Dimas Hydrologic Laboratory, California: To determine the relatio between the runoff from 19 tributary watersheds. Current.

U. S. Corps of Engineers--(1) Under supervision of the Washington District: To improve methods of stream-flow volume - duration - frequency estimates for reservoir design and to provide specific estimates for a limited number of stream gaging stations. Tables, charts, and summaries will be prepared for representative basins.

(2) California, Oregon, and Washington, under supervision of Sacramento District: Intensive studies of flood volume frequencies. Includes computation of basic data, frequency studies, and preparation of generalized charts and maps.

(3) Cooperative project between the North Pacific Division of the Corps and the Columbia Basi Inter-Agency Committee: To analyze and compare procedures of several agencies for forecasting seasonal runoff. Reports prepared on Flathead and Boise River tributaries of the Columbia River.

University of Illinois--(1) Study of runoff frequency distribution by log-probability law: An investigation on theory and application of the log-probability law to hydrologic data, particularly to runoff in streams.

(2) Runoff from small agricultural areas: An analysis of a four-year rainfall and runoff record for areas of 45, 55, 81, and 380 acres of cropland near Monticello, Illinois.

U. S. Bureau of Reclamation--Studies were made last year to determine whether basic relatio between drainage area, peak discharge, and frequency could be established and extended downward to cover the range of areas used in cross-drainage design. Except in limited zones, there were no enough data available to set up comprehensive curves.

U. S. Bureau of Public Roads--Under the supervision of the Hydraulic Research Branch: Studies to develop analytical procedures whereby short-term records of runoff may be utilized together with meteorological and topographic indices to obtain reliable estimates of peak rates of runoff for various frequencies from ungaged watersheds. Report published for two physiographic regions and others planned for future dates.

Effect of land use on runoff

U. S. Geological Survey--(1) New Mexico, under supervision of H. V. Peterson: To measure the effect of Bureau of Land Management practices on surface runoff and sedimentation in Cornfield Wash area (tributary of Rio Puerco). Started 1951. Report planned.

(2) Utah, Colorado, Wyoming, and Arizona, under supervision of H. V. Peterson: To measure the effect of Bureau of Land Management practices on surface runoff and sedimentation in Crescent Wash area, Utah; Badger Wash area, Colorado; Little Robber area, Wyoming; and Railroad Wash area, Arizona. To start 1954. Reports planned.

(3) Washington, under supervision of the Surface Water Branch: To determine effect of deforestation on runoff. Started 1945, continuing project. Report planned as open-file release.

(4) Texas, cooperative project with U. S. Soil Conservation Service: See Effect of detention basins on runoff.

U. S. Forest Service--(1) Coweeta Hydrologic Laboratory, North Carolina: Re-analysis of the results of various treated and control watersheds in which runoff is separated into ground water and storm flow. One watershed is being logged to simulate exploitation logging. The hydrologic effects of this logging will be evaluated.

(2) San Dimas Hydrologic Laboratory, California: To evaluate the effect of various watershed treatments on runoff from gaged watersheds.

(3) Arizona, Workman Creek: To compare the effect on runoff of complete logging operations versus cutting alone.

(4) Colorado, Badger Wash cooperative watershed study: To compare the effect on runoff of grazing versus non-grazing.

(5) West Virginia: To evaluate the effect on runoff of the construction of logging roads and later of complete logging operations.

New Jersey Division of Water Policy and Supply--Pine Barren Project, cooperative with U. S. Geological Survey under supervision of H. C. Barksdale, Ground-Water Division, U. S. Geological Survey: To determine the effect on runoff of converting a predominately scrub oak cover to a predominately pine cover. Project now in the third year.

Effect of detention basins on runoff

U. S. Geological Survey--(1) Wyoming, under supervision of K. R. Melin: Determination of effect of stock-water reservoirs on runoff from Cheyenne River Basin above Angostura Reservoir. Preliminary report published and final report planned on completion.

(2) Texas, cooperative project with U. S. Soil Conservation Service: To evaluate effect of flood-detention structures and land treatment practices on runoff from Honey Creek, Mukewater Creek, and Deep Creek basins.

(3) Oklahoma, cooperative project with U. S. Soil Conservation Service: To evaluate the effect of detention structures on runoff from small watersheds in the Red Plains area. Progress reports planned.

References

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TROXELL, H. C., The influence of ground-water storage on the runoff in the San Bernardino and eastern San Gabriel Mountains of Southern California, Trans. Amer. Geophys. Union, v. 34, pp. 552-562, 1953.

Bureau of Public Roads (W. D. P.),
Washington 25, D. C.

(Manuscript received May 24, 1954; presented at the Thirty-Fifth Annual Meeting, Washington, D. C., May 4, 1954; open for formal discussion until July 1, 1955.)

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MINUTES OF EXECUTIVE COMMITTEE MEETING, AMERICAN GEOPHYSICAL UNION

Meeting of December 4, 1954

The meeting was called to order at 09h 07m in the Board Room of the National Academy of Sciences - National Research Council Building, 2101 Constitution Avenue, Washington, D. C., by President James B. Macelwane.

Present--Thirty-three persons were present, namely: L. H. Adams, John Adkins, L. R. Alldredge, Wallace W. Atwood, Jr., Lloyd V. Berkner, Francis Birch, Ralph R. Bodle, Walter H. Bucher, James J. Capello, Felix Chayes, S. D. Cornell, Maurice Ewing, William F. Foshag, Charles S. Gilman, Ross Gunn, Ross R. Heinrich, Harry H. Hess, W. E. Hiatt, Benjamin Holzman, Albert J. Hoskinson, Woodrow C. Jacobs, Henry R. Joesting, Joseph Kaplan, Walter D. Lambert, John Lyman, James B. Macelwane, John Putnam Marble, James A. Peoples, Jr., Donald W. Pritchard, Richard J. Russell, A. Nelson Sayre, Waldo E. Smith, and Harold G. Wilm. The following were excused: Robert Balk, K. Hilding Beij, Hugo Benioff, Harry F. Blaney, Perry Byerly, H. R. Byers, Phil E. Church, Frank L. Culley, John A. Fleming, R. H. Fleming, J. Wallace Joyce, Esper S. Larsen, Jr., Ray K. Linsley, Gordon A. Macdonald, Walter H. Munk, Jerome Namias, Brian O'Brien, A. C. Redfield, Milton O. Schmidt, L. B. Slichter, H. T. Stetson, Victor Vacquier, Frank J. Veihmeyer, E. H. Vestine, Paul A. Weiss, and James T. Wilson.

Approval of minutes--The minutes of the Executive Committee meeting of May 2 and 5, 1954, published in the August, 1954, issue of the Transactions (pp. 681-704), were approved after deleting the statement on page 688 relative to the change in name of the Section of Terrestrial Magnetism and Electricity.

General Secretary's Report

This covers the various official activities of your General Secretary since the date of his previous report, May 5, 1954. It is essentially a factual account of matters that have arisen and of action that has been taken. Certain recommendations made to the Executive Committee for action or consideration are omitted from this published version. For convenience, this report has been divided into four sections: (1) Publications, (2) activities of the Union in its own domain, (3) activities of the Union as the American Committee of the International Union of Geodesy and Geophysics and as the Committee of Geophysics of the National Research Council, and (4) sundry matters.

Publications

Three numbers of the Transactions have been published since May 5 (June, August, and October, 1954). Each contains 160 pages. The June issue, in addition to scientific papers and other usual material, included information relative to the Sixteenth Award of the William Bowie Medal and the Union and Section minutes of the Thirty-Fifth Annual Meeting. The August issue included the minutes of the Executive Committee meetings of May 2 and 5. The total edition of the Transactions per number is now 5900.

The problem of the backlog of papers is still with us. There are indications that we will possibly receive at least a partial grant from the National Science Foundation with respect to our application to aid us in getting caught up. Such a grant will be non-recurring. The Editorial and Publication Committee has been fully cognizant of the mandate under which it was placed last spring by the Executive Committee, to reduce the interval from receipt to publication to about six months and take active steps to achieve this end. Active steps here require an expenditure of funds which up to the present have not been available. It would seem that nearly the only ways we can increase the size of the Transactions on a permanent basis and also keep the interval down to six months are through an increase in dues or a very large increase in membership, continuing at the same time to exercise increasingly severe editorial control of material accepted for publication. The majority of papers received are now sent back to the authors for condensation, and an increasing per cent has been returned, discouraging the author in the matter of modification for resubmission.

The Committee is also cognizant of the thought expressed by about one-third of those present at the Executive Committee meeting on May 5, that the present format of the *Transactions* may be an obstacle to their progress, and possibly to that of the Union. (Serious consideration has been given to this problem, and several concrete suggestions have been presented to the Executive Committee, who have taken appropriate action, as noted below.)

The December issue of the *Transactions*, consisting of 158 text pages, including the index, plus two title pages, is now in the hands of the printer.

The large volume of material, chiefly received from overseas, for use in compiling our bibliography is dispersed, after we have processed it, to the libraries of the U. S. Weather Bureau, the U. S. Coast and Geodetic Survey, and the U. S. Geological Survey with the residue finally going to the Library of Congress. In addition, representatives of the Snow, Ice, and Permafrost Research Establishment compiling a bibliography on these matters, and representatives for the meteorological bibliography compiled by the American Meteorological Society review this material to extract items which they do not secure readily through other sources, before its dispersion.

General activities

Membership--Our membership continues to grow slowly, as indicated by the following summary.

Membership as of May 1, 1954	5040	
New members, April 25 - December 1, 1954 including 50 applications now being processed	220	
Reactivated	5	5265
Resigned	49	
Dropped	125	
Inactive	4	
Deceased	17	195
Membership as of December 1, 1954		5070

The number of individual members who have paid dues in the period from January 1 to December 1, 1954, is 4556, 91 per cent of our 'paper' membership on January 1. The total was 4543 at this time last year and 4214 two years ago. Included in our 'paper' membership are 358 who have not yet paid dues in full for 1954, and 169 who have not paid dues in full for 1953 and 1954.

During the late summer and early fall a more concerted effort has been made to secure new members. This is in line with Chairman Hiatt's suggestion at the Executive Committee meeting last spring that membership can best be increased through efforts of the members, and that it might be well to institute an effort to have every member secure a new member if possible. During the summer the Editorial and Publication Committee and the President endorsed this, and initiated the effort by a letter to the members which was published on the front flyleaf of the August issue of the *Transactions*. In the intervening period about 150 applications for membership have been received, about 100 more than normally expected. The request for additional members was also noted in the closing paragraph of the card recently sent out relative to coming meetings. In connection with the publication of the Directory as Part 2 of the December issue of the *Transactions*, there will be further word on this, and an application form will be included at the back of the Directory.

At the meeting last spring 147 were reported as being delinquent in dues for whole or part of 1952 and for 1953. Of these, 21 have since paid up and are now in good standing, 13 paid dues for 1952 and entered their resignations as of December 31, 1952, two have died, and 111 have been dropped. It is possible that some of those who have been dropped will yet request reinstatement as they include names of people who should by all means be members of AGU.

The following 17 deaths have been reported since the last meeting: Clarence E. Gordon, August 28, 1951; Oswald H. Dodkin, September 7, 1953; Harold K. Barrows, March 15, 1954; Louis J. Wibert, Jr., March 17, 1954; Alfred C. Hawkins, March 30, 1954; Paul T. Seashore, April 11, 1954; Frederic W. Darling, April 21, 1954; Albert W. Giles, May 15, 1954; Edward Hyatt, June 17, 1954; Paul C. Whitney, June 19, 1954; William O. Hotchkiss, June 20, 1954; Frederick Le Verne Serviss, July 22, 1954; Thomas G. Andrews, July 23, 1954; John P. Buwalda, August 19, 1954; Samuel Whittemore Boggs, September 14, 1954; Austin Hobart Clark, October 28, 1954; and Florence Robertson, November 18, 1954. Incidentally it is noted that two of these, C. E. Gordon and Oswald H. Dodkin, have been dead for over a year and word has only come recently. Dr. Gordon was a life member, and as such paid no dues, so his Transactions continued to be sent out for more than three years after his death.

Our list of corporation members has shrunk slightly in the last year, and now includes 20 or 21 organizations (one is delinquent).

Finances--These appear to be in good shape. A financial statement was prepared as of June 30, 1954, and has been approved by the Auditing Committee. This shows that the excess of disbursements over receipts totaled $730.

At this time it would appear that items budgeted for the current year are in general sufficient to meet our regular obligations. As of December 1 the net balances in our checking account are, for 1954, $8458; for 1953, $7878; for 1952, $7000. A statement of receipts and disbursements since July 1 is available.

Office staff--This consists of J. J. Capello, Mrs. Nancy Ing, Mrs. Susan Cha, Miss Glenda Quinn, and Mrs. Beatrice L. Cone, all under the direction of Executive Secretary Waldo E. Smith.

Quarters--Our arrangements with the Carnegie Institution of Washington continue through January, 1955, and application will be made for continuation at an early date, seeing that other arrangements, such as those implied in the Berkner report, are not yet available.

Committees--There have been a number of changes in our Executive Committee. Richard J. Russell succeeds Francis Birch as Chairman of the Division of Earth Sciences of the NRC, Joseph Kaplan was elected Vice President of the Association of Geomagnetism and Aeronomy of the IUGG, and H. R. Byers was elected Vice President of the Association of Meteorology of the IUGG, and thus they become members of our Executive Committee. J. A. B. Bjerknes, formerly Vice President of IUGG; Beno Gutenberg, formerly President of the Association of Seismology and Physics of the Earth's Interior of IUGG; C. O'D. Iselin, formerly Vice President of the Association of Oceanography of IUGG; and John Verhoogen, formerly Vice President of the Association of Volcanology of IUGG have ceased to be members with the expiration of their terms. W. W. Rubey has resigned as Chairman of NRC, and thus ceases to be a member of this Committee. His successor has not been named, but S. D. Cornell is acting in his place. It should also be noted that H. G. Wilm, already on the Executive Committee, was elected Vice President of the Association of Hydrology of IUGG.

Anticipating favorable action on the Berkner report adopted last spring and published in the August issue of the Transactions, the President has appointed the Committee on International Participation: Lloyd V. Berkner, Chairman; L. H. Adams; Walter H. Bucher; Perry Byerly; Maurice Ewing; and F. W. Reichelderfer, with the President, General Secretary, and Executive Secretary acting as ex-officio members.

Honorary President John A. Fleming has stepped down as Chairman of the Committee on Award in Terrestrial Magnetism and Electricity, and has been succeeded by Ross Gunn, another member of the Committee.

Werner A. Baum, member of the Committee on Meetings for the Southeastern Region designated tentatively in 1949, conducted a survey last spring and found some interest in regional meetings and a possible regional organization in the southeastern states. Accordingly, a committee to study this matter further has been appointed under his chairmanship; J. Willard Berry, H. H. Cooper, Jr., Raphael G. Kazmann, and John C. McCampbell being the other members.

The ad hoc committee appointed in the Pacific Northwest Region arranged for a meeting which was held on November 5. A very good technical program was presented. Those present voted to organize the Region, and elected as Committee: C. C. McDonald, Chairman; V. P. Schermerhorn, Secretary-Treasurer; Peter B. Boyer; C. A. Barnes; T. H. Campbell; Fred Natella; Frank Neumann; and M. S. Sachs. Statutes and By-Laws were drawn up, presented, and approved, and have since been received by the Union office.

Meetings--As noted above, a meeting was held in Portland, Oregon, on November 5. A meeting is planned by the Pacific Southwest Regional Committee for Berkeley, California, February 4-5, 1955. This Committee voted not to join officially in the year-end meeting of the AAAS in Berkeley because that time was about six weeks removed from our traditional date, and also because of the registration fee charged by the AAAS. Members of this Committee and many other members in the area are taking part in the Berkeley meeting of the AAAS, and aiding in arrangements, and the AGU is co-sponsoring a number of symposia, as shown on the card recently sent to the membership.

A Geophysical Society of Hawaii has been organized and desires the joint sponsorship of the AGU and the AMS. The original thought was that this could operate as a local group under the already organized Pacific Southwest Regional Committee, but the latter felt that the Hawaii group should be organized as a separate Mid-Pacific Region. The Chairman of the Pacific Southwest Regional Committee recommends this, and it is satisfactory to the Hawaii group.

Plans are progressing satisfactorily for the Thirty-Sixth Annual Meeting, May 2-4, 1955. Chairman Adkins and Secretary Lill of the Committee on Meetings are arranging the general Union functions, and the Section officers have started to arrange their programs. The AMS is meeting May 4-6, inclusive, and the USA National Committee of URSI is meeting May 3-5, inclusive. Efforts are being made to integrate the three programs, as far as possible. The Joint Committee of the Sections of Meteorology and Oceanography and of the AMS, on the Interactions of the Atmosphere with the Sea is planning a symposium in connection with our meeting, probably on Storm Surges.

Non-budgetary activities--The contract for the Portsmouth Conference held last spring and that for the Bibliography of Hydrology, both cited at the Executive Committee meeting on May 2, are progressing, though slowly at the moment. These should be completed by April 30, 1955, and June 30, 1955, respectively.

International activities

Tenth General Assembly of International Union of Geodesy and Geophysics--This Assembly was held in Rome, September 14-25, 1954, with well over 1000 in attendance. One hundred sixty-four were present from the United States. An informal report on the meeting was published in the December issue of the Transactions. The President, who attended as Chief Delegate from the United States, plans to prepare a formal report later. It was decided to hold the Eleventh General Assembly in Argentina in 1957. K. R. Ramanathan of India was elected President of IUGG. The election of other officers, appointment of committees, etc., were cited in the informal report mentioned.

In the late spring the General Secretary of IUGG mailed out forms for a world directory of geodesists and geophysicists which he is compiling. No word was heard about this in Rome, but it is hoped that good progress is being made thereon.

International Geophysical Year--The International Committee on the International Geophysical Year under the chairmanship of Sydney Chapman and vice chairmanship of Lloyd V. Berkner met immediately after the Tenth General Assembly of IUGG, in Rome. Joseph Kaplan, Chairman of the U. S. National Committee, and several others from the United States attended this meeting and will report in due course.

Other international matters--The U. S. Advisory Committee on Cartography has requested the Aeronautical Chart and Information Center of the Air Force to assume responsibility for the preparation of the biennial report to the submitted to the Seventh Consultation on Cartography of the Pan American Institute of Geography and History to be held in Mexico City in March, 1955. We have been asked to aid them in compiling this report and to designate someone with whom liaison can be maintained on this matter.

A symposium on Arid Land Problems under the sponsorship of UNESCO is being organized by the AAAS to be held in Albuquerque and Socorro, New Mexico, in April - May, 1955. Everly J. Workman, member of our Committee on Meetings has been appointed as our representative. Gilbert White, one of our members, is Chairman of the Committee on Arrangements.

The Eighteenth International Geographical Congress will be held in Brazil, August 9-18, 1956. The Executive Secretary of the Congress, Hilgard O'Reilly Sternberg, one of our members in Brazil, has asked for aid in completing and correcting his list of geographers.

The Twentieth International Geological Congress is to be held in Mexico City, September 4-11, 1956. We have been able to give aid in certain details to Jorge L. Cumming, President of the Executive Committee of the Congress.

We have been informed by W. E. Blomgren, Room 10, Building 53, Denver Federal Center, that the Third Congress of the International Commission of Irrigation and Drainage will be held in the United States in April or May, 1957, probably on the Pacific Coast. We have been asked for aid and support.

National Research Council activities

Chairman Berkner of the Committee on International Participation will maintain close liaison with appropriate NRC authorities, not only as regards international participation as such, but also in the general implementation of the Berkner report approved May 2 and since published in the Transactions in August. This Committee has very broad authority.

We have continued our representation in the Division of Earth Sciences (Harry H. Hess) and, on the invitation of the Division of Physical Sciences, have appointed Walter H. Bucher as our representative thereon. Our representation on other Divisions is under discussion.

The AGU maintains its representation on the Board of Directors of the American Geological Institute through E. A. Eckhardt and Henry R. Joesting. The former has just been reappointed for a two-year term, and the latter's term has another year to run. Also, Eckhardt has been elected President and Joesting Secretary-Treasurer of the AGI.

Sundry matters

At the Executive Committee meeting on May 5 certain changes in the Statutes and By-Laws were authorized, and the matter was referred to the Committee on Statutes and By-Laws to prepare the changes in line with the principles set forth for ballot by the membership. For various reasons the whole matter was held over for review at the December meeting.

Use of travel fund--The budget sets up a fund of $150 yearly for the travel of officers. This small fund has largely been untouched in any given fiscal year. Guidance is being asked of the Executive Committee for various suggested uses thereof.

Resolutions--The Resolutions passed at the annual meeting last spring have been sent out as is customary, and numerous responses have come in from the recipients.

AAAS--Our affiliation with the AAAS continues. We sponsored or co-sponsored several sessions at their meeting last winter. At the present time our representatives on its Council are L. B. Slichter and J. P. Marble.

American Standards Association--We were formerly represented on Committee PH2 on Photographic Sensitometry. Upon the recommendation of Fred Anderegg of the University of Michigan, our representative, this has been discontinued. Another Committee, on Fluid Permeation, under the chairmanship of our representative C. E. Jacob, has not reported recently, and its activity at present is not known.

News items--At the inauguration of Edwin Ruthen Walker as President of Queens College, Charlotte, N. C., we were represented by Werner A. Baum. At the dedication of the Quartermaster Research and Development Center at Natick, Massachusetts, October 14, we were represented by Milton Greenberg. We were unfortunately unable to send representatives to the inauguration of the new President of Beloit College or to the Twenty-Fifth Anniversary ceremonies of the Waterways Experiment Station at Vicksburg, Mississippi. We regret to say that, because of the confusion attendant upon the absence in Rome of the officers of the Union, we neglected to appoint a representative for the dedication of the Boulder Laboratories of the National Bureau of Standards on September 14.

On November 12 and 13 the Mapping and Charting Research Laboratory of Ohio State University held a Symposium on the New Era of Geodesy. No report has been received, but it was anticipated that many geodesists would be in attendance.

During the early summer, the Union office reviewed the report "Manpower Resources in the Earth Sciences" and returned this with comments to the Commissioner of Labor Statistics in the Department of Labor.

The microcard project of the Microcard Foundation and the Micro-sortcard project of the Petroleum Research Company are continuing in accordance with arrangements made and under conditions specified by our Editorial and Publication Committee.

We have offered to Choji Magono of the Yokohama National University in Japan, through the bibliography on hydrology now being compiled under contract, and through our Committee on Snow, aid on a bibliography he is compiling on snow-melt studies. This also applies to other organizations at work in this field.

In conclusion, I am deeply indebted to our President for wise and timely advice, and to many members for advice, suggestions, and criticisms. Without the constant assistance and support of our Executive Secretary, Waldo E. Smith, I would not have been able to do anything.

John Putnam Marble, General Secretary

Action on the General Secretary's report--The report was accepted.

Action on recommendation of the General Secretary--It was approved that the travel item of $240.51 withdrawn from the Emergency Fund, as noted, be replaced by a transfer from the General Fund in order that the Emergency Fund may remain intact.

International matters

Tenth General Assembly of the International Union of Geodesy and Geophysics--President Macelwane, Chief Delegate to the Assembly that was held in Rome, September 14-25, 1954, mentioned that on the evening of September 13 a meeting of the American delegation was held in the Grand Hotel in Rome and that about 30 were present. The delegates were briefed with regard to the developments to date, and their assistance on all matters relating to the Assembly was requested. Specific assignments were made to the Section delegates for reports relating to the activities of those Sections, and reports were requested from all delegates as an aid in the preparation of the report to be prepared by the Chief Delegate. Among the items discussed was the schedule of dues paid to the IUGG, the fact that we had received no agenda for the business meetings of the IUGG or any of its Associations, that we had no information with regard to the budget of the IUGG or its Associations, the next meeting place of IUGG, problems concerning the Continental Shelf, and the matter of new officers for the IUGG and its Associations. It was noted that a registration fee was being charged to those listed as guests, but that no registration fee was being charged to delegates. The American delegation took the stand that an equal fee should be charged to all.

There was extensive discussion regarding the unwritten rule that officers of the Union should be rotated among the various fields of geophysics and the various member nations, and it was moved and passed that we express our concern over the continued use of this rule without time limit and that there should be a nine-year limit on this so that a country who, for example, has supplied a President to IUGG might again supply a President after a lapse of nine years.

The President also reported that the State Department made available to the Chief Delegate a small fund for the entertainment of foreign delegations. With the cooperation of the American Embassy a reception was held to which the Chief Delegates from all countries were invited. The small remainder of the fund was used for a luncheon at which the officers, new and old, of the International Union were the honored guests.

The President noted that the physical facilities for the Assembly were unusually favorable, all the meetings having been held under one roof, that the transportation problem to and from the Assembly grounds was in general well handled, and that the programs of the individual Associations were of a very high order but very full, with numerous sessions held simultaneously.

W. W. Atwood, Jr., Director of the Office of International Relations of the National Research Council, reported that the meetings were generally favorable from the scientific standpoint but that the business aspects were not well handled due perhaps in large part to the absence of agenda for the Union and its Associations.

International Geophysical Year--Joseph Kaplan, Chairman of the U. S. National Committee for the International Geophysical Year, made a brief report on the progress of plans for the International Geophysical Year, including the developments in Rome. He pointed out that the papers of the symposium on the scientific aspects of the IGY presented at the meeting of the National Academy of Sciences in the spring of 1954 have now been published in the Proceedings of the Academy. He mentioned that the Bureau of the Budget has approved the entire program through 1955, that Congress has made a preliminary appropriation to initiate the work, and that the program is currently entering the operating stage. He pointed out that the Navy ice-breaker Atka was already on route to the Antarctic on initial phases of the program and mentioned that increasing participation by AGU and other organizations is important.

L. V. Berkner, Vice Chairman of the ICSU Committee on the International Geophysical Year, said that the following priority of operations during the current year has been established: (1) setting up world-wide network for synoptic measurements, (2) those programs that would depend upon available synoptic measurements, (3) epochal observations where these are possible, and (4) observations at locations where these are not ordinarily available. A concentration of effort is being made in the Arctic, the Antarctic, and on the Equator.

Seventh Consultation on Cartography of Pan American Institute of Geography and History--In accordance with the request of the Aeronautical Chart and Information Center of the Air Force, it was noted that Albert J. Hoskinson, President of our Section of Geodesy, is now active in the work of collaboration in this for the U. S. Coast and Geodetic Survey, and accordingly he was designated as our representative to maintain liaison in the compilation of the biennial report from the United States to be submitted to this conference to be held in Mexico City in March, 1955.

Reports of Standing Committees

Editorial and Publication--The President outlined the current problem as follows: At the meeting of the Executive Committee on May 2, 1954, there was very strong sentiment expressed that our present Transactions format is an obstacle to the progress of our Transactions and perhaps to AGU. At the meeting of the Executive Committee on May 5 the Editorial and Publication Committee was charged with the problem of reducing the backlog of papers so that the interval from receipt to publication would average about six months. During the intervening months these matters have been the subject of serious thought and discussion by the Editorial and Publication Committee, and it was realized that only by the expenditure of funds not available currently could steps be taken to overcome these difficulties. As noted, an application to the National Science Foundation for a grant to aid in getting caught up on our backlog is under consideration, and, while this, if the grant is received, should help in the immediate problem, it is not a long-term solution. These matters were extensively discussed and it was pointed out that if we simply justified the right-hand margin using the same type fonts as at present, this would involve the purchase of a second electromatic typewriter and take perhaps a half to three-fourths of the time of another electromatic typist, and the cost would thus be considerable. It was felt that possibly letterpress or some one of the newer processes involving the photographic preparation of copy for offset should be adopted. The thought was quite generally expressed that not only should we justify the right-hand margin but that we should produce a publication that approaches letterpress publication in appearance. To accomplish this improvement in format and to maintain a shorter time lag after the present backlog is decreased, it was finally agreed that we should publish the Transactions by letterpress or something close to it in appearance, that we maintain a publication interval averaging about six months from receipt to publication, and that the funds to accomplish these things should be raised by the following means: (1) Increase the dues from $7.00 to $8.00 per year, (2) increase the gross revenue from reprints to about double their cost, (3) solicit dignified display advertising, and (4) if these are insufficient, make a per-page charge for publication. It was noted that the National Research Council has approved our acceptance of display advertising germane to geophysics.

Statutes and By-Laws--In the absence of K. Hilding Beij, Chairman of the Committee, the report of the Committee was presented by Ralph R. Bodle. The report recommended approval in principle of the Statutes and By-Laws of the newly organized Pacific Northwest Region, and this recommendation was accepted. (A few minor items are being clarified with the Region, following which this portion of the report and the Statutes and By-Laws of the Region will be published in the Transactions.) The report also recommended approval in principle of the establishment of the Geophysical Society of Hawaii as a Mid-Pacific Regional Branch of AGU, detached from our Pacific Southwest Region and under the joint sponsorship of AGU and the American Meteorological Society, and the approval of the Constitution and By-Laws of the Branch. This recommendation was accepted. (Following the clarification of a few details by the Pacific Southwest Region and the Mid-Pacific Region, this portion of the report, and the Constitution and By-Laws of the Mid-Pacific Region, and the necessary changes in the Pacific Southwest Region's Statutes and By-Laws, will be published in the Transactions.)

The Committee also recommended changes in the Statutes and By-Laws of the Union. The recommendations with minor modifications were accepted as presented in Appendix 1, and action was taken to place the changes in the Statutes before the National Research Council for further action and the changes in the Statutes and By-Laws before the membership by ballot.

President Macelwane reported receiving a letter from Chairman Beij requesting that he be relieved of his duties as Chairman of the Committee on Statutes and By-Laws but remaining as a member of that Committee. Beij recommended that Ralph R. Bodle, already a member of the Committee, be designated as Chairman in his place. Bodle was appointed.

Meetings--Chairman Adkins reported that the Thirty-Sixth Annual Meeting will be held May 2-4, 1955. It is anticipated that a symposium on ice will be held as the main portion of the general program of the Union, part of this to be presented on the evening of the Award of the Bowie Medal and part on the afternoon preceding the business meeting of the Union. He mentioned also that a meeting of the Pacific Southwest Region is scheduled to be held in Berkeley, California, February 4-5, 1955.

Membership--Chairman Hiatt made a comparison of AGU membership for a number of years, pointing out that from April, 1947, to April, 1948, 1460 new members were brought in largely as the result of one very active member of the Committee. He also presented data on the gross growth in comparison with the net growth in the membership. He felt that a most substantial growth can be attained through the active participation of the whole membership in this matter and that it was in line with this philosophy that the every-member-get-a-member effort was undertaken. He mentioned that the hoped-for growth had not been realized but that continued tactful urging of the membership over a period of time should be helpful. It was mentioned that the tieing in of this activity with our regional organizations should prove to be helpful in the long run.

Audit--Chairman Sayre presented the report of the Committee as shown in Appendix 2. The report was approved.

Reports of Special Committees

Cosmic-Terrestrial Relationships--Chairman Stetson was unable to attend, but the brief report that he had transmitted is as follows:

The Committee on Cosmic-Terrestrial Relationships has continued its activities. Korff conducted a series of balloon flights in Minnesota in which the neutron intensity at high elevations was measured. Measurements were also made at the station on Mt. Wrangell, Alaska. Riehl has developed a short method of predicting the path of hurricanes. He has recently visited the High Altitude Observatory at Boulder, Colorado, and left in November for Japan where he is attending a UNESCO typhoon conference in Tokyo. Your Chairman has also been in correspondence with Chairman Sargent of the Committee of Bioclimatology of the American Meteorological Society.

Corporation Memberships--Chairman Eckhardt was not able to attend, but reported that he anticipates the beginning of active search for new corporation members within the next two or three months.

Award in Terrestrial Magnetism and Electricity--Chairman Gunn reported that more than $3000 have been promised and that $215 are already in hand and on deposit. He indicated that he planned to proceed with the raising of an additional amount and feels that this might be done quite quickly after the Committee gets this matter organized.

Reports of Sections

The President called on the various Sections for comments, noting especially that comments were requested relative to the meeting in Rome.

Geodesy--President Hoskinson reported that he attended as many sessions as possible and was impressed with the way the Association of Geodesy is organized, particularly with respect to the working groups which carry on the activity in the three-year periods between meetings. He stated that a good deal of time was utilized by reports from the chairmen of these working groups and that the number of formal papers was relatively small. He felt that there is a great advantage in having international working groups. He noted that other nations designate the same delegates to these meetings time after time and that there is better continuity in the delegations of many countries than in the case of the United States. In Geodesy continuity will be preserved by sending at least one member from the Coast and Geodetic Survey to each meeting in the future who has been in attendance at one or more meetings in the past.

Seismology and Physics of the Earth's Interior--President Heinrich of the Section of Seismology reported the chief difficulty was that occasionally more than one session was in progress in Seismology at one time, noting that important papers thus were sometimes given simultaneously. He felt that one of the biggest troubles in the Association of Seismology is the matter of financing and noted that the Association was against the proposal that the publications of the Association be put in the hands of a commercial publisher.

President Birch of the Section of Tectonophysics noted that some of the most interesting sessions were joint sessions and that he felt that these should be encouraged. He thought that the business sessions had a tendency to take too much time. Noting the difference between the various fields, President Macelwane pointed out that Geodesy can perhaps function as it does because it is very largely an organization of government workers in the various countries while the workers in Seismology and the Physics of the Earth's Interior are much more dispersed throughout the population in the various countries.

Terrestrial Magnetism and Electricity--Secretary Alldredge was unable to attend the meeting in Rome and President Vacquier was not in attendance at the Executive Committee meeting, and Joseph Kaplan, newly elected Vice President of the Association which had changed its name to the Association of Geomagnetism and Aeronomy, reported that from his point of view the symposium on the aspects of the upper atmosphere was the most important but that some of the other sessions included very interesting papers and sometimes were not very well attended. He felt that part of this was because of conflict, not by concurrent sessions of a given Association, but by conflict between Association programs.

Oceanography--John Lyman, alternate designated by President Fleming, noted that Fleming was elected Secretary of the International Association of Physical Oceanography.

Volcanology--J. P. Marble reported that, at many of the sessions, he was the only American in attendance. He pointed out that there were several very interesting joint sessions at which important and interesting papers were given by persons not primarily volcanologists in the classical sense. He noted that all papers presented by Canadians were available in mimeographed form.

Hydrology--President Wilm reported that over 200 papers were presented on the program, which were far too many. He was impressed by the fine arrangements and excellent meeting place and the hospitality of the people. He felt that American scientists are in the vanguard with regard to scientific hydrology, and that the meetings are fine in the establishment of personal contacts.

Walter H. Bucher, Past President of AGU and Chief Delegate at the meeting in Brussels, said that he was struck by the absence of geologists and the apparent lack of close cooperation between geologists and geophysicists in Europe. He felt that we should do what we can to overcome this and that it would be helpful if more geologists were specifically invited to these meetings.

Affiliated Organizations

American Association for the Advancement of Science--J. P. Marble, one of our representatives, noted a letter from L. B. Slichter (our other representative) concerning the meeting in Berkeley, December 27-31, 1954. Slichter was in charge of arrangements for one of the three symposia on the general topic Science and Society, namely, the one on Natural Resources. In addition, AGU cosponsored other symposia as follows: Soil management problems in western agriculture; Water supplies and irrigation; and Earth sciences from the air.

American Geological Institute--H. R. Joesting, reporting for himself and E. A. Eckhardt, noted that they had attended a meeting of the Institute on October 30. Eckhardt was elected President and Joesting was elected Secretary-Treasurer for the year ending October 31, 1955. He mentioned that a committee has been appointed to consider the recommendations of AGU [see Report of Committee on Statutes and By-Laws, Trans., v. 35, pp. 688-689, August, 1954].

Adjournment--The meeting adjourned at 13h 41m.

John Putnam Marble, General Secretary
Waldo E. Smith, Executive Secretary

APPENDIX 1--REPORT OF THE COMMITTEE ON STATUTES AND BY-LAWS

K. Hilding Beij, Chairman

Ralph R. Bodle John A. Fleming

Item (1) relates to the Statutes and By-Laws of the Pacific Northwest Region, and Item (2) to the establishment of a Mid-Pacific Region. These will be published subsequently upon the clarification of details.

(3) In accordance with the approvals of the Executive Committee of the Union and of the Section of Volcanology, it is recommended that the first paragraph in Article 4 of the Statutes of the Union be amended to read as follows:

Article 4: Sections--The American Geophysical Union shall consist of Sections as follows: (a) Geodesy; (b) Seismology; (c) Meteorology; (d) Terrestrial Magnetism and Electricity; (e) Oceanography; (f) Volcanology, Geochemistry, and Petrology; (g) Hydrology; (h) Tectonophysics.

(4) As the Executive Committee of the Union has approved the addition of the grade of student membership, it is recommended that the following paragraph be added to Article 3 of the Statutes of the Union [for earlier consideration of this matter see Report of Special Committee, Trans., v. 31, pp. 648-649, August, 1950]:

(f) Student Members--College and university students elected by the Executive Committee. A certificate signed by an officer or professor of the institution attended shall be submitted annually as qualification. The classification of a student member shall terminate after one year of non-student status, and if judged to be qualified by the Executive Committee, the former student shall be an Associate Member on his own written acceptance. Student members shall be privileged to participate in scientific meetings and receive the Transactions of the Union.

And that the following sentence be added to paragraph (2) of the By-Laws (for complete amended form of this paragraph see Item 8 of this report):

Members of class (f) shall pay annual dues approximating the cost of a volume of the Transactions, the amount for each year to be fixed by the Executive Committee.

And that the first paragraph of By-Law (20) shall be amended to read as follows:

(20) One copy of each issue of (a) the Transactions, (b) any published List of Members and Officers, and (c) any other publication which may be approved for free distribution to the membership by the Executive Committee of the Union, shall be sent to each Member, Associate, and Corporation Member whose annual dues for the calendar year have been paid by July 1; any person or organization newly elected as Member, Associate, or Corporation Member shall be sent without charge one copy of these publications beginning with the calendar year in which elected and for which dues have been paid. Each member on a retired basis, Member ex officio, and Corresponding Member shall be accorded this privilege also. Each Student Member shall receive one copy of each issue of the Transactions for each year of paid membership.

(5) In accord with the Report of the Special Committee on Relations between the American Geophysical Union and the National Research Council [see Trans., v. 35, pp. 691-699, August, 1954], it is recommended that paragraph (3) of the By-Laws be amended to read as follows:

(3) Standing Committees shall be as follows: Statutes and By-Laws; Membership; Meetings; Nominations; Budget; Audit; Editorial and Publication.

There shall also be a standing Committee on International Participation consisting of the President, the General Secretary, and the Executive Secretary of the American Geophysical Union and six additional persons (not necessarily AGU members) who are eminent geophysicists with knowledge and background in international organization and cooperation. The Committee shall be appointed at the first meeting of the Executive Committee following each Assembly of the IUGG, and shall serve for a term of three years to include the interval of the next Assembly. The Committee, acting on behalf of the Executive Committee, shall (a) recommend to the Office of International Relations, NRC, the organization of delegations to the Assemblies of the IUGG and to such other international meetings as may be appropriate; (b) review all administrative questions that might or should be raised at, or may be related to, international meetings or assemblies with the view of fully informing our delegations of the implications thereof; (c) advise the NRC Foreign Policy Committee, or the NRC Committee on International Unions, on matters of international science policy relating to geophysical science; and (d) advise the Executive Committee of the AGU of all actions taken or initiated. The Committee shall take full account of the broad interests of geophysical science in the United States, and of the various organizations and agencies involved in geophysical activity.

It is also recommended that the second paragraph of Article 7 of the Statutes be amended to read as follows:

This Committee shall have charge of all administrative matters of the American Geophysical Union and shall be the representative of the Union in its relations with the National Research Council and the International Union of Geodesy and Geophysics. It shall have the power to delegate to the Officers and to Standing and Special Committees, with power of action and decision, any of its specific functions.

(6) In view of the changes in the organization of the National Research Council and the National Academy of Sciences, it is recommended that paragraph (b) of Article 3 of the Statutes be amended to read as follows:

(b) Members ex officio--(1) The President of the National Academy of Sciences; the Chairman of the National Research Council; the Chairman of the Section of Geophysics of the National Academy of Sciences; the Chairmen of the following Divisions of the National Research Council: Earth Sciences, Physical Sciences, Chemistry and Chemical Technology, and Biology and Agriculture; and the Director of the Office of International Relations of the National Research Council.

(2) Officers of the International Union of Geodesy and Geophysics and of its Associations who are citizens of the United States of America.

It is also recommended that the first paragraph of Article 7 of the Statutes be amended to read as follows:

Article 7: Executive Committee--The Executive Committee of the Union shall consist of the President, the Vice President, and the General Secretary of the Union, and of the President or his designated representative and the Secretary of each Section of the Union, the last past Presidents of the Union and its Sections, the Chairmen of the Standing Committees of the Union; and, in addition, ex officio, the Honorary President, the Executive Secretary of the Union, and members ex officio as listed in Article 3 (b) of these Statutes.

(7) It has been suggested to the Committee that the provisions for amending the By-Laws are too rigid. It is therefore recommended that Article 13 of the Statutes be amended to read as follows:

Article 13: Amendments--(a) Any Member, Associate, or Corporation Member may propose an amendment to the Statutes. Such proposals shall be considered by the Committee on Statutes and By-Laws and presented to the Executive Committee of the Union with recommendations. Upon approval of the Executive Committee, proposed amendments shall be submitted to the membership for a mail vote. Balloting shall be open for not less than 30 days. A majority of the votes cast shall be required for adoption. Amendments shall be subject to the approval of the National Research Council.

(b) Any Member, Associate, or Corporation Member may propose an amendment to the By-Laws. Such proposal shall be considered by the Committee on Statutes and By-Laws and presented to the Executive Committee of the Union with recommendations. Upon approval of the Executive Committee, proposed amendments shall be published in the Transactions not less than 30 days prior to action at a succeeding meeting of the Executive Committee. Action must be completed within a year after publication. Approval by the Executive Committee at this meeting shall constitute adoption of the amendments. An affirmative vote of not less than half the membership of the Executive Committee shall be required for approval.

(8) It has been suggested to the Committee that paragraph (2) of the By-Laws is too restrictive in that possible changes in the size and format of the Transactions might require some adjustment of dues. It is therefore recommended that paragraph (2) of the By-Laws be amended to read as follows:

(2) Members of the Union, in classes (a) and (d) of Article 3 of the Statutes, shall pay dues, the amount for each year to be fixed by the Executive Committee of the Union. Members of class (e) shall pay dues of not less than $100 for each calendar year. Any Member or Associate, on payment of not less than $100 at any time, the amount to be fixed by the Executive Committee of the Union, shall be relieved of further payment of dues. Members of class (f) shall pay dues approximating the cost of a volume of the Transactions, the amount for each year to be fixed by the Executive Committee.

APPENDIX 2--REPORT OF THE COMMITTEE ON AUDIT

Fiscal Year July 1, 1953, to June 30, 1954

A. Nelson Sayre, Chairman
A. G. McNish R. H. Weightman

Your Committee on Audit has examined the books of the American Geophysical Union for the fiscal year ending June 30, 1954, and finds them in agreement with the statement of the Union's finances supplied by the General Secretary.

Operating Statement

(Fiscal year ending June 30, 1954)

Receipts			
Grant			
National Research Council			$ 400.00
Income			
Dues, 1951 and earlier	$ 180.50		
1952	308.00		
1953	3,528.94		
1954	27,248.45		
1955	133.50		
1956 et seq.	17.00		
Corporation Memberships	2,000.00		
Life Membership	100.00	$33,516.39	
Sales of publications			
Transactions	$ 7,612.67		
Reprints	2,059.34		
Index of *Transactions* (1920-1944)	16.00		
Miscellaneous	11.85	9,699.86	43,216.25
Contributions to the Permanent Fund			339.00
Interest on Permanent and Emergency Funds			254.82
Contributions for T. M. and E. Award			210.00
Interest on T. M. and E. Award Fund			1.66
Science Register			470.47
Air Force Contract			2,321.58
Miscellaneous			37.98
			$47,251.76
Disbursements			
Publishing *Transactions*			
Printing		$11,405.09	
Preparing master copy		9,288.73	
Honoraria to editors		1,250.00	
Mailing		895.61	$22,839.43
Reprints			1,959.06
General expenditures (office of the Union)			
Salaries (including Federal Social Security)		$14,599.55	
Stationery and supplies		744.31	
Postage and communications		1,190.96	
Office equipment		200.99	16,735.81
Expenses, meetings			
Annual meeting		$ 846.50	
Regional meetings		92.65	939.15
Expenses, Section of Hydrology			3.90
Expenses, Committees (Membership, $63.95; other, $4.89)			68.84
William Bowie Medal			13.70
Air Force Contract			2,632.19[a]
Science Register			470.47[a]
T. M. and E. Award (investment, deposited with Liberty Building Assn. $210.00 plus $1.66 interest December 9, 1953, to June 30, 1954)			211.66[a]
Miscellaneous			477.64
Investment: Interest July 1, 1953, to June 30, 1954, from Prudential Building Assn. as part of Emergency Fund			33.67[a]
Investment: Deposited with Northwestern Federal Savings and Loan Assn. as part of Permanent Fund, $1,375.00, plus interest July 1, 1953, to June 30, 1954, $221.15			1,596.15[a]
Total disbursements			$47,981.67
Transfer from Cash Reserve to Reserve for Directory			900.00
			$48,881.67

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[a] Non-budgeted items.

Excess of disbursements over receipts

Disbursements		$47,981.67
Receipts		47,251.76
	Decrease in liquid funds	$ 729.91

Statement of assets and liabilities as of June 30, 1954

Assets			
Cash Reserve	$14,292.32		
Reserve for Directory	900.00		
Robert E. Horton Fund	1,180.91	$16,373.23[b]	
Permanent Fund			
Series F bonds purchased prior to July 1, 1948 (maturity value $3,200), at cost	$ 2,368.00		
On deposit in Northwestern Federal Savings and Loan Assn. as shown for July 1, 1954	8,289.52	10,657.52	
Emergency Fund			
On deposit in Prudential Building Assn. as shown for July 1, 1954		1,061.36	
T. M. and E. Award			
On deposit with Liberty Building Assn. as shown for July 1, 1954		211.66	$28,303.77
Bills Receivable			
Dues			
1954 only	$ 4,965.10		
1953 and 1954	2,616.00	$ 7,581.10	
Publications			
Transactions (including subscriptions)	$ 412.05		
Reprints	461.83		
Miscellaneous	47.95	921.83	8,502.93
Air Force Contract Receivable			389.28
			$37,195.98
Liabilities			
Bills Payable and advance payments			
Dues in advance (1955 et seq.)		$ 141.00	
Subscriptions in advance (1955 et seq.)		111.30	
Reprints paid in advance		49.60	$ 301.90
Surplus (Capital Account)			36,894.08
			$37,195.98

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[b] Riggs National Bank statement of June 30, 1954	$20,331.42
Less checks outstanding	3,958.19
Net balance June 30, 1954, as above	$16,373.23

At the beginning of the current fiscal year the Cash Assets of the Union amounted to $17,103.14. These assets consisted of $15,922.23 held as Cash Reserve and $1,180.91 in the Robert E. Horton Fund. The two Funds are carried in a single account in the Riggs National Bank. The Permanent Fund amounting to $9,061.37 consisted of $2,368.00 invested in Series F Bonds and $6,693.37 on deposit in the Northwestern Federal Savings and Loan Association. (See Trans., v. 35, pp. 343-345, April, 1954, for Statement of Assets and Liabilities as of June 30, 1953.)

The receipts for the year totalled $47,251.76, while the expenditures totalled $47,981.67; thus the Liquid Assets were decreased by $729.91. It was found possible to increase the Permanent Fund by additions to our account in the Northwestern Savings and Loan Association of $1596.15 in Cash and Accumulated Interest, making a total of $10,657.52 as of July 1, 1954. This amount includes a total of $339.00, graciously contributed to the Permanent Fund by individuals during the year. The Emergency Fund established last year in accordance with the desires of the Executive Committee was increased by the addition of earned interest to $1,061.36 as of July 1, 1954. A new item appears among the assets of the Union with the establishement of a fund for an award in Terrestrial Magnetism and Electricity. Gifts to the fund plus accumulated interest amount to $211.66. At the end of the year the Cash Assets of the Union were $16,373.23, a decrease of $729.91. Of this amount $1,180.91 was credited to the Horton Fund. An amount of $900.00 was held in reserve for the Directory.

REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

NAGATA, TAKESI, Rock-Magnetism, Maruzen Co., Ltd., Tokyo, xii + 225 pp., 1953.

Many advances have been made in both the physical and the petrological aspects of this topic since Koenigsberger's writings systematized the field less than a generation ago. The present author deals comprehensively with the various constituent minerals that are considered responsible for the magnetic properties of rocks, the equipment used for evaluating the various parameters, and the remanent and thermo-remanent magnetization, including his own contributions to the development of theories to account for remanent magnetization that is contrary to the observed direction of the ambient field.

The book opens with a 20-page outline of ferromagnetism that is a gem of conciseness and clarity, extending to such topics as the Curie points of alloys, magnetic anisotropy, magnetostriction, domain structure, Rayleigh loops, and the magnetic properties of small grains. Next antiferromagnetism and ferrimagnetism are dealt with, and then specific minerals are considered. This brief synopsis of Chapter I indicates the thoroughness of coverage; the next four chapters are equally painstaking, and the last one (on geophysical problems) serves as an excellent introduction to the related disciplines of paleomagnetism and the interpretation of magnetic anomalies.

DAVID G. KNAPP

MARSHALL, C. E., and H. NARAIN, Regional Gravity Investigations in the Eastern and Central Commonwealth, Department of Geology and Geophysics, University of Sydney, mem. 1954/2, 101 pp., 1954.

A reconnaissance regional gravity survey of the eastern tectonic belt of Australia and central Australia has been accomplished. Nearly 1000 gravity stations have been established over traverses covering approximately 10,000 mi. In the Eastern Commonwealth there is evidence of (a) variation in crustal thickness, (b) gentle regional crustal warping, and (c) superimposed effects due to either local crustal sag or to 'root' formation in the regions of the 'tectogenes.' In central Australia the regional anomalies have established the existence of major east-west structural features in response to north-south compressional forces operating during Precambrian times. These forces have apparently resulted in the formation of a 'horst' block of Arunta Complex in the region immediately north of Alice Springs and a crustal 'sag' in the Amadeus Basin. In Queensland, residual anomalies show close agreement with the structural elements of the State as proposed by Dorothy Hill.

Gravity traverses over batholiths in New South Wales and in Queensland have revealed interesting characteristics. They generally fall in two classes, one which indicates deep 'roots' and is generally formed by fusion at the bases of geosynclines. Evidence of the other type is provided by the traverse from Bega to Spencer's Creek where granitization probably took place by metasomatism of the pre-existing rocks in situ.

THE AUTHORS

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NOTES AND PERSONALIA

NOTES

Icebreaker Atka on preliminary work on the International Geophysical Year--The U. S. Navy icebreaker Atka sailed from Boston, Massachusetts, on December 1, 1954, for Antarctica via Panama and Wellington, N. Z., to conduct preliminary reconnaissance in connection with U. S. participation in the Antarctic program of the IGY. W. L. Tressler of the U. S. Navy Hydrographic Office is in charge of the oceanographic program on the cruise. The expedition will return in April, 1955.

Cosmic-ray experiments in Texas--In January, the Office of Naval Research and the Atomic Energy Commission began a program of the release of high-altitude plastic balloons with apparatus for the gathering of data on cosmic rays, the work taking place at Goodfellow Air Force Base at San Angelo, Texas. The Skyhook constant-level balloons, ranging up to 90 ft in diameter, will carry as much as 150 lbs. of equipment and rise to 90,000 or 100,000 ft, and remain at these heights for several hours. Scientists from the University of Minnesota, University of Chicago, University of Iowa, and other schools will participate.

Fellowships and assistantships in Oceanography and Meteorology at Texas A and M College--Graduate fellowships and assistantships, with stipends ranging from $2000 to $3000 will be given by the College for the academic year 1955-1956. One undergraduate scholarship with a stipend of $500 and student assistantships will be available for undergraduates. Interested persons should write to the Department of Oceanography, Texas A and M College, College Station, Texas. Applications should be submitted by March 30, 1955.

French Bibliographical Digest--The Permanent Representative of French Universities in the United States has announced the availability, without charge to libraries and university departments, of the third issue of the second series of the Digest. This relates to geology and was compiled by Louis Glangeaud of the University of Besançon. A companion volume including geophysics is now under preparation. Interested persons should write to the Cultural Division of the French Embassy, 972 Fifth Avenue, New York 21, N. Y.

Recent grants of the National Science Foundation--The recent grants announced by the National Science Foundation included the following: radiocarbon dating, University of Chicago (W. F. Libby, two years, $20,000); physical properties of clouds, University of Arizona (R. H. Braham, Jr., two years, $50,000); origin of low-frequency geomagnetic fluctuations, University of California (R. E. Holzer, one year, $9400); silicate systems, University of California (G. C. Kennedy, two years, $15,000); fabric of experimentally deformed ionic crystals and rocks, University of California (F. J. Turner, two years, $13,000); isotopic abundances relating to geochemical research, University of Chicago (H. C. Urey, one year, $21,000); geochemical investigations of sedimentary rocks, Massachusetts Institute of Technology (W. H. Dennen and E. Mencher, one year, $10,300); crystal structures of minerals, Massachusetts Institute of Technology (M. J. Buerger, two years, $24,000); structural mineralogy of the serpentine group of minerals, Pennsylvania State University (G. W. Brindley, one year, $10,000); phase rule and polymorphism, Pennsylvania State University (R. Roy, three years, $30,000); travel-time studies and development of improved travel-time curves for the Pacific Ocean region, U. S. Coast and Geodetic Survey (D. S. Carder, two years, $15,000); tectonic history of the region around Lake Mead, Nevada-Arizona, Yale University (C. R. Longwell, one year, $3500); cause of motion in the aurora, Cornell University (H. G. Booker and B. Nichols, two years, $13,300); unsteady flow in smooth pipes, Georgia Institute of Technology (M. R. Carstens, two years, $13,800); composition of the stars, University of California (O. Struve, two years, $21,000); and microschmidt reddened B-star survey, University of Chicago (A. B. Meinel and W. W. Morgan, 18 months, $13,000).

Fellowships and assistantships, New York University--Two fellowships carrying full tuition and fees and a cash stipend of $2500 are available for 1955-1956 for study in meteorology or oceanography. Also available are a number of assistantships in these fields providing work from ten to 20 hours per week at rates varying from $1.85 to $2.30 per hour. Applications should be filed by April 1, 1955. For forms and other information, write to the Graduate Division, College of Engineering, New York University, New York 53, N. Y.

Geodimeters now under test in the United States--Five geodimeters, developed by Erik Bergstrand of Sweden, have been acquired by the Engineer Research and Development Laboratories of the U. S. Army. These are currently under test, two by the Laboratories, one by the Army Map Service, one by Army Ordnance, and one by the U. S. Coast and Geodetic Survey. This device measured distances up to about 50 miles with great accuracy, using the velocity of light as a basis. It was first developed in 1948 and was demonstrated at the Ninth General Assembly of IUGG in Brussels in 1951.

Study of Caribbean waters--The research vessels Atlantis and Caryn of Woods Hole Oceanographic Institution left on a four-month cruise to Caribbean waters in January. An extensive study will be made of the bedrock below the sea bottom by seismic means, studying the thickness of the overlying sediment. Charles B. Officer, Jr., is the chief scientist on the cruise. Extensive studies will also be made of the fertility and productivity of the waters. A new underwater camera with an acoustical 'viewfinder' will be used in the work to learn more about the 'scattering layers.' Near the end of March, the scientific personnel will leave the ships in St. Thomas, V. I., and a different group under J. B. Hersey will take over for work in the Bahamas and the Carolina coast.

Publication of Curie papers--The Polish Academy of Sciences has announced the forthcoming publication of the complete original texts of the scientific papers of Maria Sklodowska-Curie, who, with her husband, Pierre, discovered radium in 1898. This is part of the commemoration of the twentieth anniversary of her death.

College student work study program--The Board of U. S. Civil Service Examiners for Scientific and Technical Personnel for the Potomac River Naval Command and the Engineer Center of the U. S. Army announce the availability of summer positions for student trainees at the rate of $2750 to $3175 per year in various fields of science, including oceanography, meteorology, cartography, physics, and engineering. Applicants should file form 5000AB with the Board, Building 37, Naval Research Laboratory, Washington 25, D. C., as promptly as possible.

Cruise of the R. V. Brown Bear--A group of scientists from the Department of Oceanography of the University of Washington under the leadership of Robert G. Paquette made a six-week cruise of the Gulf of Alaska during August and September, 1954, to obtain a general picture of oceanographic conditions in this area during the summer months. Sixty stations were occupied between 52°N, 154°W and the coast of North America, and measurements were made of salinity, temperature, dissolved oxygen, and inorganic phosphates to depths up to 5000 m, and a continuous echo sounding was made over the entire course. Circulation and current data were also gathered. The work was sponsored by the Office of Naval Research.

Meeting of the USA National Committee of URSI--The Spring Meeting of this group will be held during the same week as the AGU meeting in Washington, D. C., May 3-5, 1955. Interested persons should write to the Secretary, William E. Gordon, School of Electrical Engineering, Cornell University, Ithaca, N. Y.

Symposium on Electromagnetic Wave Theory--This Symposium will be held at Ann Arbor, Michigan, June 20-25, 1955, under the joint sponsorship of the University of Michigan and Commission VI (Radion Waves and Circuits) of the International Scientific Radio Union. Interested persons should write to the Symposium Chairman, K. M. Siegel, Willow Run Research Center, University of Michigan, Ypsilanti, Mich.

Meeting of the Joint Commission on the Ionosphere--A meeting of this Commission of the International Council of Scientific Unions will be held in London, August 22-24, 1955. Interested persons should write to the Secretary, W. J. G. Beynon, Department of Physics, University College of Swansea, Singleton Park, Swansea, England.

PERSONALIA

W. A. Heiskanen, Scientific Director of the Mapping and Charting Research Laboratory of Ohio State University, has returned to the Finnish Geodetic Institute for a seven-month period until August, 1955. R. A. Hirvonen of Finland will take over his courses during his absence.

W. C. Krumbein has been granted a leave of absence from Northwestern University to study statistical methods in geology. He will spend several months as guest worker on problems of statistical design at the National Bureau of Standards in Washington, and about two months at Princeton University as Research Associate in the Department of Mathematics and Visiting Fellow of the Geology Department.

Charles B. Officer, Jr., Geophysicist of the Woods Hole Oceanographic Institution, has been designated the distinguished lecturer for 1954-1955 of the Society of Exploration Geophysicists, and during December and January presented lectures on seismic exploration of ocean areas before the local sections of the Society.

Paul B. Sears of Yale University has been named President Elect of the American Association for the Advancement of Science.

Willis L. Webb has left his work in the Physical Research Division of the U. S. Weather Bureau to take up duties with the Atmospheric Research Group of the Signal Corps at the White Sands Proving Ground, N. Mex.

John C. Beebe, Special Assistant on hydraulic engineering problems with the Federal Power Commission, retired, died in Coeur d'Alene, Idaho, December 13, 1954, at the age of 68. He was born at Hampden, Massachusetts, and took his baccalaureate degree at Dartmouth College in 1909, and a professional degree in civil engineering from the University of Wisconsin in 1910. His early professional career was devoted to western water problems with various organizations, and in 1915-1916 he was engaged on the flood-control work of the Miami Conservancy District in Ohio. He was associated with the U. S. Forest Service from 1929-1939, and from 1939 until his retirement in 1948 was with the Federal Power Commission. He had been a member of AGU since 1943.

Bernard A. Etcheverry, Professor Emeritus of Irrigation Engineering of the University of California, died October 26, 1954, in New Haven, Connecticut, at the age of 73. He was born in San Diego, California, and received his baccalaureate degree from the University of California in 1902, at which time he became a member of the staff of the school. He served as Head of the Department of Irrigation Engineering from 1905 until his retirement in 1951. He had served as consultant on numerous projects, and is well known throughout the world for his authoritative books on irrigation. He had been a member of AGU since 1931.

SPECIAL ANNOUNCEMENTS

Thirty-Sixth Annual Meeting, Washington, D. C., May 2-4, 1955--Attention is called to previous announcements regarding this meeting that have been published in the Transactions, especially that in October, 1954, page 865, relating particularly to program matters, and that in December, 1954, page 1017, giving information on the block booking of hotel rooms. Program details are rapidly being settled, and some sections had their programs almost complete in late January. The program officially closes March 10, 1955, so time is now short for those who desire to have their papers included in the program. Three copies of the titles and abstracts should be in by March 10, 1955 (as set forth in the October announcement), with word covering amount of time desired (ten to 20 minutes usually allowed) and projection equipment needed. Filled programs will be closed in advance of March 10.

The "every-member-get-a-member" effort--This effort was initiated by a letter to the membership from President Macelwane printed on the front flyleaf of the Transactions of August, 1954, and by a direct letter from Chairman Hiatt of the Committee on Membership in September. While the response to this effort has been substantial in the way of applications received and the names suggested, it has not attained the proportions hoped for. We feel there are still many well-qualified persons who should be interested in membership if the matter is called to their attention. Perhaps you are one of those who has already acted in this regard. If you are, keep up the good work. If not, won't you please do what you can - and become an active member of the Committee of Five Thousand. To facilitate this, an application form will be found at the back of this issue.

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THE ELECTRICAL CONDUCTIVITY OF THE EARTH'S MANTLE

S. K. Runcorn

Abstract--The rapid rise in electrical conductivity at depths of 700 km in the Earth's mantle, inferred by S. Chapman and his collaborators from a study of the transient variations of the geomagnetic field, may be well explained on the hypothesis that the process of intrinsic semi-conduction is of importance in this region. H. Hughes of the Department of Geodesy and Geophysics, Cambridge University, has demonstrated the various conduction processes occurring in olivine and similar minerals and has shown that the results fit in quantitatively with the observational data referred to above. An indirect method of estimating the effect of pressure on the process of intrinsic semi-conduction has been attempted and does not appear to alter the view that the rapid rise in conductivity is, in essence, a temperature effect. From this work estimates can be made of the electrical conductivity of the lower part of the mantle, which agree with estimates inferred from the spectrum of the secular variation of the geomagnetic field and the explanation of the irregular fluctuations in the length of the day.

Introduction--The problem presented by the existence of the main geomagnetic field has been thought by some writers, notably ELSASSER [1939, 1946, 1947], BULLARD [1949], and BULLARD and GELLMAN [1954], to be that of finding some mechanism to produce electromotive forces within the Earth's core. The high density of the core suggests that it has a metallic character, with a high electrical conductivity, which makes it a likely seat of the electric currents responsible for the magnetic field. Furthermore, its fluid character makes it possible to provide, through thermal convection, the mechanical energy necessary to supply the energy lost in Joule heat by the electric currents and the changes of magnetic energy associated with the geomagnetic secular variation. ELSASSER [1939] first attempted to use the temperature differences in the Earth's core to produce thermoelectric forces between elements of the fluid with different thermoelectric constants, arising from the pressure differences developed in maintaining the motion. He was, however, able to show that such an effect was likely to be far too small. ELSASSER [1946, 1947], BULLARD [1949], and BULLARD and GELLMAN [1954] have discussed how, in a conducting sphere in which motions are maintained, a field can build up by electromagnetic induction--the problem of the existence of homogeneous dynamos.

RUNCORN [1954] has introduced into the discussion the new possibility that electromotive forces may exist on the spherical boundary between the core and the mantle and that therefore the problem of the geomagnetic field is one in which it is essential that the lower part of the mantle have considerable electrical conductivity and that some of the electric currents responsible for the main geomagnetic field flow between the core and the mantle. This paper discusses the theory of the distribution of the electrical conductivity in the mantle. In fact, the work described in this paper was begun in order to investigate the plausibility of the author's thermoelectric theory of the main geomagnetic field.

Conductivity of insulators at high temperatures--BIRCH [1952] has examined the observed variation of the seismic velocities with depth in the mantle in the light of that expected on the basis (partly) of the theory of solids and (partly) of experiments on highly compressible solids at high pressures. He concludes that at depths greater than 900 km the mantle is chemically homogeneous. Its composition he takes to be close-packed oxides, possibly a high-pressure modification of the ferromagnesian silicates found higher up in the mantle. VERHOOGEN [1954], however, finds the evidence not inconsistent with an olivine composition for the whole of the mantle, apart from the crust. At any rate there is no seismic evidence which makes it likely that the mantle contains an appreciable amount of metallic material. If UREY's [1952] view is correct that the separation of the iron core is still proceeding and that an appreciable amount of iron is retained in the lower part of the mantle, it is likely to be in lumps embedded in the silicates. Thus, the electrical conductivity of the mantle is likely to result from the effect of temperature and pressure on silicates or oxides, which are insulators at low temperatures.

Much recent work on the theory of solids has been concerned with the behavior of semi-conductors (for instance see MOTT and GURNEY [1948]). Any insulator, even without impurities in solid solution, will possess an appreciable electronic conductivity at elevated temperatures, termed intrinsic semi-conduction. In a solid, the allowed energy levels familiar in the theory of atomic spectra broaden into energy bands, containing many levels, each of which, by Pauli's principle, may only be occupied by two electrons. In an insulator, these bands do not overlap; at low temperatures, the levels in the valency band are completely occupied and those in the conduction band are entirely empty. Thus, the crystal can carry no current. As the temperature is increased, some of the electrons are raised into the conduction band and may then receive energy from an applied electric field, thus constituting a flow of current.

The conductivity σ is given by the formula

$$\sigma = \sigma_0 \exp(-E/2kT) \qquad (1)$$

where E is the excitation energy of the process, that is, the difference in energy between the highest level of the valency band and the lowest level of the conduction band, k is Boltzmann's constant, and T is the absolute temperature.

The conductivity at very high temperatures approaches σ_0 which is nearly independent of temperature and is given by

$$\sigma_0 = 2n^{1/2} (2\pi mkT/h^2)^{3/4} ev$$

when n is the number of valency electrons per cubic centimeter, e and m are the electronic charge and mass, v is the mobility of the electrons, and h is Planck's constant.

HUGHES [1953] describes experiments carried out in the Department of Geodesy and Geophysics at Cambridge, which demonstrate the existence of intrinsic semi-conduction in olivine and other minerals. In fact, such minerals appear to be among the few solids in which intrinsic conductivity may be demonstrated, as usually the excitation energy is so large that other types of conductivity mask its effect at temperatures below the melting point. Hughes finds that in general two other types of conduction are of importance in these minerals under laboratory conditions, that is, impurity semi-conduction and ionic conduction. The former has too small a value of σ_0 to produce a conductivity of consequence except perhaps in the crust. This is fortunate, as the effects of high pressure on this process would probably be very great, for the energy levels of impurity atoms are likely to depend strongly on the lattice spacing of the crystal. Conduction by the movement of ions has a value of σ_0 about 10^6 times greater than intrinsic semi-conduction, and so will become more important than the latter at some temperature at ordinary pressures. However, the high pressures obtained in the Earth's mantle will probably effectively inhibit ionic conduction, since ions will find it much more difficult to move through a lattice that has been reduced in size by pressure than will electrons. Unfortunately, it is difficult at the moment to discuss this possibility quantitatively, and in this paper it will be assumed that intrinsic conduction is the only effective process throughout the mantle. This is, however, little better than a plausible guess. The proposal that intrinsic conduction is effective throughout the mantle below a certain depth can be tested against the inferences drawn from geomagnetic phenomena.

Empirical knowledge of the electrical conductivity of the mantle--The direct knowledge of the electrical conductivity of the Earth's mantle, apart from the crustal layers, arises from the analysis of the periodic and aperiodic geomagnetic changes of external origin, mainly the solar daily variations and magnetic storms. Knowing the distribution of such fields over the Earth's surface, it is possible by Gaussian analysis to effect their separation into parts of internal and external origin. The internal part is assumed to be induced by the external part, and a comparison of the two leads to inferences about the conductivity down to the greatest depth of penetration of the induced currents. The latest discussion is due to LAHIRI and PRICE [1939], who conclude that the conductivity must lie in the space between d and e in Figure 1. This shows that the electrical conductivity of the mantle, apart from the high surface value due to the oceans, must remain less than 10^{-3} mho/cm down to a depth of 700 km. It must then increase very rapidly to at least 10^{-2} mho/cm at a depth of 900 km. Lahiri and Price were inclined to attribute their result to a change of chemical composition, corresponding to the evidence of a discontinuity in the seismic velocities between depths of 200 km and 900 km. This suggestion does not explain why minerals have appreciable electrical conductivity, nor does it provide any reason to expect a very much higher conductivity in the lower part of the mantle, which has now become an important feature of the theory of geomagnetism.

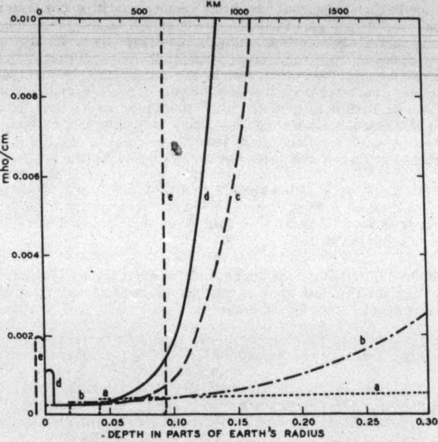

Fig. 1--Distribution of conductivity within the Earth compatible with transient geomagnetic fluctuations (after Lahiri and Price)

To account for the irregular fluctuations in the length of the day, it is necessary to assume a loose electromagnetic coupling of the core and mantle. The theory (Runcorn, manuscript in preparation) indicates a conductivity of approximately 1 mho/cm in the lower part of the mantle. A much higher conductivity would prevent relative motion of the core and mantle, whereas a much lower value implies excessively large electromotive forces in the mantle.

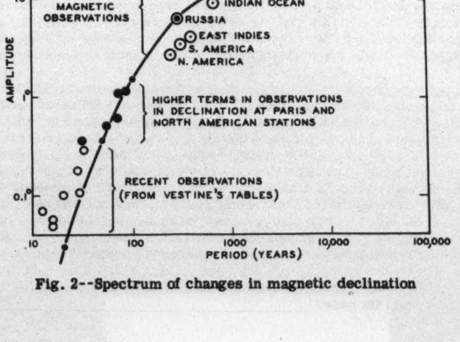

Fig. 2--Spectrum of changes in magnetic declination

The geomagnetic secular variation--Any theory of the electrical conductivity of the mantle must also take into account the spectrum of the geomagnetic secular variation. That the mantle might be sufficiently conducting to attenuate by an appreciable factor the more rapid components of the secular variation has been suggested by many geomagneticians, particularly by A. T. Price (personal communication). At any rate the conductivity cannot be too great; otherwise the field variations in the lower part of the mantle would be excessively large. HUGHES and MOORE [1955] have made Fourier analyses of data from recently established observatories, from early measurements, and from the palaeomagnetism of varved clays. In this way they find the spectrum reproduced in Figure 2. In fact, each spherical harmonic of the secular-variation potential has its own spectrum, but sufficient data prior to 1900 are not available for such a detailed representation, and one must assume that Hughes and Moore's spectrum is largely that of those harmonics of orders 2-4, which Vestine and his collaborators have shown to be predominant in the last fifty years. It is convenient to represent the spectrum by the empirical expression

$$A = 40 \exp(-13.2\sqrt{\omega})$$

where ω is the angular frequency (in years^{-1}). This curve is shown on Figure 2 to fit Hughes and Moore's spectrum reasonably well.

As only the lower half of the mantle is appreciably conducting, it is sufficient to approximate the screening problem to one of an infinite plate of thickness L and conductivity σ at distance ℓ_c from one surface. Then the screening is given by the expression

$$A(\omega) = A_o(\omega) \exp\left[-\int_o^L \left(\frac{2\pi\sigma\omega}{3\times10^7}\right)^{1/2} d\ell\right]$$

where A is the amplitude of the eastward horizontal intensity (or declination) at the Earth's surface in degrees, and A_o is the corresponding amplitude at the base of the mantle.

If a mean conductivity $\bar{\sigma}^{1/2} = (1/L)\int_o^L \sigma^{1/2}\, d\ell$ is defined, then

$$A = A_o \exp[-(2\pi\bar{\sigma})^{1/2}(\omega^{1/2}/5620)L] = A_o \exp[-3.35\times10^{-4}(\bar{\sigma})^{1/2}(\omega)^{1/2}L]$$

Thus

$$A_o = 40 \exp\left\{\omega^{1/2}[3.35\times10^{-4}(\bar{\sigma})^{1/2}L - 13.2]\right\} \quad \ldots\ldots\ldots\ldots\ldots (2)$$

Thus for the spectrum of the secular variation at the bottom of the mantle to be independent of frequency

$$\bar{\sigma}L^2 = 1.1\times10^9$$

For this to be true, if the lower 1000 km of the mantle is assumed to be uniformly conducting, its conductivity becomes 1.1×10^{-7} emu or 110 mho/cm. Thus the electrical conductivity of the mantle is less than this figure if the amplitude of the original spectrum of the secular variation decreases with period. While this is a satisfactory result in that the reverse of this situation is hard to envisage, a close upper limit to the conductivity of the mantle can clearly not be found in this way.

A feature of the secular variation noticed by various workers [HAZARD and McFARLAND, 1937; HOWE, 1941, 1942; and WALKER and O'DEA, 1952] and examined particularly by MOORE [1954] is the suddenness of changes in rate of the secular variation. There are large changes which become effective within a few years at the most. It has sometimes been supposed, particularly in extrapolating the values of the geomagnetic field in certain areas for the purpose of making maps, that the rate of the secular variation changes but slowly with time. This assumption is by no means borne out by a careful investigation of observatory records, as Moore shows. It is in some cases possible to represent the annual mean values of field components from observatory data by a series of straight lines, the secular variation rate being assumed to undergo sudden changes. Walker and O'Dea came to similar conclusions and termed the phenomena 'secular-change impulses.' It is not possible yet to discuss their significance in any detail, but it is possible to set an upper limit to the mean conductivity of the mantle using the fact that such sharp changes must be presumed to come up through the mantle from its base.

Consider the mantle as an infinite sheet of uniform thickness L and conductivity σ. We may examine how the growth of a uniform field on one side proceeds if a uniform field of unit intensity parallel to the sheet is suddenly produced at time $t = 0$ and maintained with the same intensity for all time on the other side of the sheet.

Let the z axis be taken perpendicular to the sheet and the y axis parallel to the sheet. Maxwell's equations for this problem reduce to

$$(d^2 H_y/dz^2) - 4\pi\sigma\,(dH_y/dt) = 0$$

Using the method of Laplace-transforms, the subsidiary equation is

$$(d^2 \bar{H}_y/dz^2) - k^2 \bar{H}_y = 0$$

where $k^2 = 4\pi\sigma p$. This is to be solved with the following boundary condition at $z = 0$

$$H_y = \begin{cases} 0 \text{ for } t < 0 \\ 1 \text{ for } t > 0 \end{cases}$$

or

$$\bar{H}_y = 1/p$$

$$\bar{H}_y = A \cosh kz + B \sinh kz$$

At $z = 0$, $A = \bar{H}_y = 1/p$. At $z = L$, $d\bar{H}_y/dz = 0$.

$$A \sinh (kL) + B \cosh (kL) = 0$$

$$B = -A \tanh (kL)$$

$$\therefore \bar{H}_y = (1/p) \cosh (kz) - (1/p) \tanh (kL) \sinh (kz) = (1/p) [\cosh k(z - L)/\cosh (kL)]$$

At $z = L$

$$\bar{H}_y = (1/p) [2/e^{kL} (1 + e^{-2kL})] = (2/p) (e^{-kL} - e^{-3kL} + \dots)$$

Thus

$$H_y = (2/\sqrt{\pi}) (-\operatorname{erf c} \sqrt{\pi\sigma}\, L/\sqrt{t} + \operatorname{erf c} 3\sqrt{\pi\sigma}\, L/\sqrt{t} \dots)$$

where erf is the error function or probability integral, and erf c is the complementary error function, or 1 - erf.

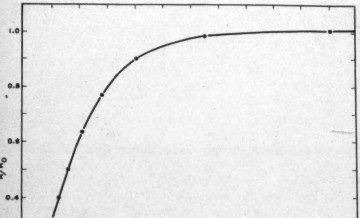

Fig. 3--Growth curve for the surface field after a sudden change at the base of the mantle (two-dimensional model)

Figure 3 shows this solution plotted against time, expressed in units of $\sqrt{\pi\sigma}$ L. From this curve, showing the growth of the field at the Earth's surface arising from a sudden jump in the field at the surface of the core, we conclude that sudden changes in the rate of the secular variation cannot become established in times less than $\sqrt{\pi\sigma}$ L. Four years may be taken as an upper limit of this time. Thus the mean value of σL^2 cannot exceed 10^7 emu. If the lower 2000 km of the mantle only is appreciably conducting, this results in a maximum mean conductivity of 1 mho/cm.

Physical theory of the electrical conductivity of the mantle--Because of the chemical composition of the mantle, it is reasonable to examine how far the simple process of intrinsic semiconduction will explain the distribution of electrical conductivity with depth in the mantle. Now, σ_0 for intrinsic semi-conductors is often about 10 mho/cm. That the mean electrical conductivity of the lower mantle must be about 1 mho/cm and that this conductivity cannot fall off severely in the lower 1000 km of the mantle suggest that we may be dealing with an insulator in which a high proportion of the available electrons are fully excited.

There are two distinct hypotheses about the temperature in the deeper parts of the mantle. **JEFFREYS** [1952] supposes that the Earth was originally molten, cooling by convection. He shows it to be reasonable that solidification began at the core-mantle boundary and progressed outwards. Each layer of solid acted as a thermal insulator to material below, so that the temperature in the deeper parts of the mantle remained at the melting point of olivine at that pressure. By extrapolation from laboratory experiments, one arrives at a temperature of 10,100°K at the core-mantle boundary with a temperature gradient of 3°C/km. **UFFEN** [1952] modifies the melting point gradient with depth by using seismic data to compute the characteristic frequency of vibration of the crystal lattice at various depths. These are then related to the melting point by a theory of fusion. He obtains a temperature of 5200°K at the boundary with a temperature gradient, uniform below a depth of 900 km, of 0.8°C/km.

Alternatively one may suppose that the mantle is in slow convection, then the temperature gradient is the adiabatic gradient. **VERHOOGEN** [1954] on this basis gives the temperature at the core-mantle boundary as 2600°K and the temperature gradient as 0.26°C/km.

One finds that none of these estimates provides a large enough difference in temperature to explain by intrinsic semi-conduction such wide differences in conductivity as a value of 1 mho/cm at the mantle-core boundary and a value of 10^{-2} mho/cm at a depth of 900 km as indicated from curve d of Figure 1. However, Price and Lahiri show that the conductivity curve lies somewhere between curves d and e, and we shall find it necessary to assume that the electrical conductivity at a depth of 900 km is much in excess of the value considered above.

We shall assume that the temperature T at height ℓ from the core boundary is given by the expression $T = T_c (1 - \alpha\ell)$ when T_c is the temperature at the core boundary. Then it is simple to show that the mean conductivity between the boundary and a depth of 900 km is

$$\bar{\sigma}^{1/2} = (4kT_c/E\alpha\ell)\,(\sigma_c^{1/2} - \sigma_1^{1/2})$$

where σ_1 is the conductivity at a depth of 900 km. Jeffrey's data give $\alpha = 0.3$ per 1000 km, Uffen's data give $\alpha = 0.15$ per 1000 km, and Verhoogen's data give $\alpha = 0.1$ per 1000 km.

Now

$$\bar{\sigma}^{1/2}/\sigma_o^{1/2} = (4kT_c/E)\,[\exp(-4kT_c/E)]\;\;(1/\alpha L)\,[1 - \exp(E\alpha L/4kT_c)]$$

Taking σ_o as 10 mho/cm, a reasonable value for an intrinsic semi-conductor, the value of $E/4kT_c$ may be calculated for different values of α such that $\bar{\sigma} = 1$ mho/cm. E may be then calculated for each temperature distribution as shown in Table 1.

Table 1--Calculation of E

α	T_c	$E/4kT_c$	E	σ_c	σ_1
	°K		ev	mho/cm	mho/cm
0.1 (Verhoogen)	2,600	1.05	0.92	1.17	0.77
0.15 (Uffen)	5,200	0.97	1.80	1.2	0.4
0.3 (Jeffreys)	10,100	0.90	3.28	1.9	0.18

The values for σ_1 show that the sudden rise of the electrical conductivity between depths of 700 and 900 km must be interpreted on this picture probably in terms of a phase change in which there is a sudden decrease of E, which is to be expected when the lattice is rearranged so that the atoms are more closely packed. Still supposing that ionic conduction is suppressed, the conductivities above this layer could be well explained by intrinsic semi-conduction in olivine. **HUGHES** [1953] has shown from his experiments that at ordinary pressures E lies between 2 and 3 ev.

So far we have ignored the effect of pressure upon E. The fractional change of this with depth is likely to be of the same order as the fractional change in the lattice spacing, which can be determined from seismic data. Between a depth of 900 km and the core-mantle boundary, the density rises at a uniform rate of 0.54 gm/cm^3 per 1000 km. In this region the mean density is 5.14, thus the fractional change in lattice constant is 0.035 per 1000 km. Comparing this with the above values of α, it seems reasonable to ignore the effect of pressure on intrinsic semi-conduction in comparison with that of temperature. Laboratory measurements (Runcorn, publication in preparation) give support to the view that the proportional change in lattice dimensions and the proportional change in the value of E are of the same order of magnitude.

The electrical conductivity of the core--It is now possible to arrive at the spectrum of the secular variation at the base of the mantle. Putting $(\bar{\sigma}^{1/2} L) = 10^{7/2}$ in (2), we obtain

$$A_0 = 40 \exp(-12.2\,\omega^{1/2})$$

That the amplitude of the secular variation depends on frequency in this form is not surprising. The geomagnetic secular change arises from the interactions of motion in the Earth's core with primary magnetic fields, which do not appear outside the Earth. The characteristics of such electromagnetic induction depend on a non-dimensional constant, and we should expect the secular variation spectrum to be some function of this constant. The constant is $\omega^{1/2}\,\sigma^{1/2}\,x$, where σ is the electrical conductivity of the core, which is estimated by ELSASSER [1947] to be 1000 mho/cm, and x is a scale length connected with the eddies associated with the secular variation. If we could calculate this spectrum, we should begin with Maxwell's equations in electromagnetic units and the hydrodynamic equations. None of these differential equations contain coefficients of an order different from unity, thus it is reasonable to equate the observed exponent in the equation of the spectrum with the non-dimensional constant. Thus $x = 300$ km. It seems hard to believe that the scale of the motions producing the secular variation is so small. LOWES and RUNCORN [1951] show that the pattern is probably produced by current loops, 3000 km in diameter. If x is put equal to this, σ falls to 10 mho/cm. It is thus suggested that the electrical conductivity of the core may be smaller than the value which has been accepted on the basis of extrapolation from laboratory data.

Acknowledgments--It is a pleasure to acknowledge the stimulating discussions with my colleagues in the Department of Geodesy and Geophysics, particularly H. Hughes, F. J. Lowes, P. H. Roberts, A. F. Moore, and D. C. Tozer, on various aspects of this work.

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THE MT. SPURR ERUPTION, JULY 9, 1953

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[a]Deceased

(Publication authorized by the Director, U. S. Geological Survey)

Abstract--The July 9, 1953, eruption of a subsidiary cone of Mt. Spurr, Alaska, is of particular interest because the initial phases were under close observation by the crews of two jet aircraft which were in the vicinity when the eruption started. Within one hour the eruption cloud assumed a mushroom shape which reached an altitude of approximately 70,000 ft. Extremely heavy rains accompanying the eruption, and water supplied by the melting of ice in the immediate vicinity of the vent, caused flash floods which carried sufficient debris to dam one of the major rivers in the area and form a lake nearly five miles long. A one-quarter-inch blanket of ash was deposited on the city of Anchorage, 80 mi from Mt. Spurr; but, in the opposite direction, no discoloration of snow fields and glaciers could be seen within two or three miles of the volcano. Observations of this eruption of Mt. Spurr particularly emphasize the importance of prevailing wind direction in the control of ash-fall distribution resulting from an eruption of this type.

Introduction--At 05h 00m on July 9, 1953, a subsidiary cone on the south flank of Mt. Spurr west of Anchorage, Alaska, erupted a dark vulcanian cloud of ash and vapor to a height of approximately 70,000 ft. The ash cloud, carried by gentle westerly winds, reached Anchorage by noon, plunged the city into total darkness, and deposited a quarter of an inch of fine dust over the city.

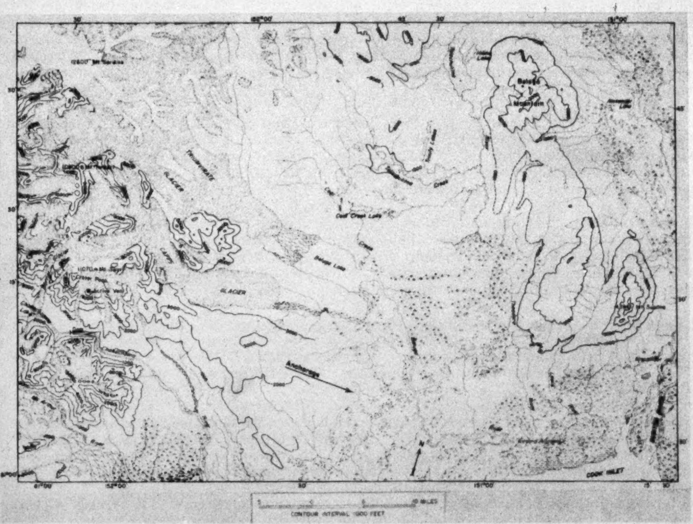

Fig. 1--Index map of the Mt. Spurr region

The writers were engaged in field work in southwestern Alaska in the Katmai area and were assigned to investigate the volcano. They were flown on a reconnaissance mission over the volcano at 04h 00m on July 11 and later in the day were landed near Mt. Spurr to study the area from the ground until July 14. Another trip was made by helicopter to the active volcano on July 16.

Geographic and geologic setting--Mt. Spurr lies on the east flank of the Alaska Range, approximately 80 mi west of Anchorage and 125 mi southwest of Mt. McKinley. It is the northernmost volcano of the 1500-mi Aleutian volcanic belt, which extends through the Alaska Peninsula and includes Mt. Spurr, Mt. Redoubt, Mt. Iliamna, Mt. Augustine, Mt. Katmai, Mt. Trident, Mt. Martin, and others. Its snow-capped peak is one of 76 volcanoes recognized in this belt [COATS, 1950].

Mt. Spurr itself is the highest of several volcanic peaks in a massif that covers approximately ten square miles. Extensive ice fields and snowfields cover the high flanks of the mountain. Andesitic flows and pyroclastic breccias from these volcanoes overlie a basement complex of granite and quartz diorite. Locally, thick breccias consisting of blocky lava boulders as much as two feet in diameter enclosed in a finer tuffaceous matrix are interbedded with or overlie the distal portions of the flows. The deposits are poorly sorted and unstratified and appear to be the depositional products of volcanic mudflows, that is, lahars.

Most of the Mt. Spurr mass is a large dissected volcanic structure whose chief vent lies at the present summit. A much fresher subsidiary cone is located on the south flank overlooking the Chakachatna River. The major ice fields and snowfields of Mt. Spurr lie north of the subsidiary cone, and extensive glaciers border the eastern and western flanks of the cone. The cone consists chiefly of andesitic flows but includes minor quantities of tuff-breccia and other pyroclastic rocks. The crater rim is approximately 7000 ft above sea level and about half a mile in diameter. Photographs of Mt. Spurr taken prior to July 9, 1953, show a continuous ice cap on the subsidiary cone with small glaciers extending short distances down the flanks.

CAPPS [1935, pp. 69-70] suggested that Mt. Spurr might be a central cone built inside an older, very large caldera breached in places by glaciated valleys. Our observations indicate, however, that Mt. Spurr is simply one of a complex group of individual volcanic cones and granitic peaks and that the postulated gigantic caldera rim is only a fortuitous arrangement of discrete mountain peaks of dissimilar origins. The dips of lava flows and pyroclastic beds on the flanks of individual peaks composing the eastern arc of the postulated crater rim are quaquaversal, which indicates extrusion from a series of separate vents rather than from a single central feeder. Moreover, the individual peaks composing the western arc of the supposed crater rim consist entirely of granitic rocks.

Eruption of 1953--During the past three decades a vapor plume has issued from the summit of Mt. Spurr at irregular intervals. Pilots reported an increasing discharge of steam from the peak during the late spring of 1953. The subsidiary parasitic cone on the southern flank of Mt. Spurr, however, had never been reported to be active. Nevertheless, this parasitic cone was the center of volcanic activity during the eruption of July 9, 1953.

Detailed observations of the initial stage of the eruption were made by four Air Force airmen flying early morning jet patrol in the vicinity. These observations are unique not only because the pilots were close at hand during the early phases of the eruption but also because ground radar fixes maintained on the two planes of the patrol during the time of the observations provided a close check of the estimated dimensions of the volcanic cloud.

The following is the official Air Force account [U. S. AIR FORCE, 1953]:

Lieutenant Mark J. Metzner of Chicago, Illinois, pilot, and Lieutenant Robert A. Fasula of Las Vegas, New Mexico, radar observer of one plane; Captain Ross Reese, Albuquerque, New Mexico, pilot, and Lieutenant James Ranni, New York City, radar observer of the other plane, all members of the Alaskan Air Command, were on early morning patrol. At 05h 05m Lieutenant Metzner noticed a column of smoke 60 mi ahead that was about 15,000 ft high and one-eighth of a mile wide. As he approached the smoke, it was apparent that the eruption causing it was becoming increasingly severe with the smoke growing rapidly in height. At about 25 mi distance, the volcano was recognized as the 11,070-ft high Mt. Spurr. Both planes approached the mountain about 15,000 ft and circled the volcano at about 05h 25m. They noticed the continuing increase in the intensity and size of the column of smoke with lightning flashes through its core every 30 sec. Smoke issued from the volcano in violent billows at the 7000-ft level of the mountain caused by huge subterranean explosions. Tremors on the mountainsides were visible from the aircraft and were followed by snow slides on the mountain. The smoke had by now reached the 30,000-ft level, rolling upward and assuming the shape of the atomic bomb mushroom. Clouds of smoke were every shade of gray from black at the crater to pure white at the top. By this time the width had increased to about a mile at the base and 30 mi at its widest part.

About 05h 40m Lieutenant Metzner climbed in order to estimate the height of the mushroom. The top of the stalk, or the bottom of the mushroom, was 30,000 ft and the top of the mushroom had climbed to 70,000 ft. Lightning was now flashing from top to bottom of the mushroom at three-second intervals.

At about 06h 00m volcanic ash began falling from the mushroom on all sides and finally made the entire area hazy. A clear definition of the volcano and the mushroom rapidly faded and the patrol returned to its base.

One jet plane that flew through the cloud had its plexiglass cockpit canopy frosted on the outside by the 'sandblasting' action of the ash.

Coarse lapilli fell near the volcano, and west winds blew finer ash and dust eastward in the direction of Anchorage. Records supplied by the Air Weather Service show very gentle westerly winds at all altitudes on July 9. Glaciers and mountains two to three miles to the south, north, and west of the volcano were left entirely free of ash, the white snow appearing in marked contrast to the black ash-covered glaciers east of the volcano. Volcanic dust fell in sufficient abundance in the lowland area west of the Susitna Flats and southeast of Beluga Lake to bend down small alders and ferns.

The cloud of finely pulverized volcanic ash reached Anchorage at about 12h 00m and plunged the city into darkness, but the haze began to diminish by late afternoon. A quarter inch of very fine dark rock powder was deposited in Anchorage, disrupting air traffic for nearly two days. The dust extended to Valdez, to Gannett Peak east of Anchorage, and to within 30 mi of Cordova. Palmer, Kenai, Kalgin Island, and Tuxedni Bay near Mt. Iliamna received only a slight film of ash. The effects of the ashfall in the Anchorage area were studied by WILCOX [1953] of the U. S. Geological Survey.

Winds, whipping up fallen dust, caused a second-cycle duststorm in Anchorage and vicinity on July 15. From July 9 to 15, small whirlwinds spiraling narrow columns of dust several hundred feet high and dusty trails raised by running moose were erroneously reported as signs of fumarolic action in the lowland area west of Beluga Lake and in the vicinity of Mt. Susitna, a granite ridge west of Anchorage. Several Alaska Range peaks, including Mt. Torbert and Mt. Gerdine, were also erroneously reported as active. Normal clouds were mistaken for condensed steam plumes from these peaks, which are not volcanoes.

Close observation of the subsidiary cone between July 11 and 16 showed that ice both on the inner and on the outer slope of the crater was still largely intact after the eruption, although it was covered by black pyroclastic debris to depths of several inches. Only in the central part of the crater, where the actual vent formed, was the ice completely destroyed. The southern flank of the continuous ice rim was partly breached, with castellated ice pinnacles standing in sharp relief within the breached zone. There were no observable fracture systems or fumarolic zones peripheral to the single central vent. White clouds of condensed steam still issued from the central vent and rose to altitudes of 20,000 ft. Small quantities of black dust and rock debris were occasionally hurled into the air from the vent, but most fell back into the volcanic throat. One particularly vigorous steam puff at 14h 00m on July 13 was followed by a single sharp thunderclap, but this was the only noise associated with the eruption after the initial violent outburst. No lava flows were produced, nor was there any characteristic odor or incandescence perceived during the period of observation.

The initial eruption was accompanied by torrential rains in the immediate vicinity of the volcano. The heavy precipitation as well as rapid melting of ice adjacent to the vent resulted in flash floods on tributary streams running into the Chakachatna River and the carrying of large boulders and blocks of ice as much as ten feet in diameter into the valley. The mud line on brush high on the slopes of the steep-walled tributaries indicated that gorges normally carrying water only one or two feet deep were filled to depths of 40 or 50 ft. Where the floods issued from the narrow steep-walled canyons and spread over a river terrace of the Chakachatna, alder bushes were stripped away as though uprooted by a bulldozer. The accumulated flood debris was swept across the channel of the Chakachatna River to form a natural dam that backed up the river for nearly five miles, flooding mature spruce forests along the shores. By July 11 the water level of the lake had fallen 15 ft from its initial high owing to the partial removal of the natural dam. The present spillway across this dam, however, is now paved by a lag concentrate of large boulders, consequently, the level of the new lake may be expected to remain at the July 11 level for a considerable time.

The observations of Mt. Spurr emphasize the importance of meteorological conditions in controlling the ash fall distribution resulting from a volcanic eruption of this type and also illustrate the profound disruption of the local drainage regimen that may be occasioned by volcanism.

Acknowledgments--The cooperation of the U. S. Air Force made possible the detailed observation of this eruption. Particular appreciation is due Lieutenant General Joseph H. Atkinson, U. S. A. F., Commander-in-Chief, Alaskan Command, and Major General George R. Acheson, U. S. A. F., Commander, Alaskan Air Command, for authorizing the use of facilities and equipment that were under their commands and that were required for this operation.

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A COMPARATIVE ANALYSIS OF WIND-TUNNEL AND ATMOSPHERIC AIR-FLOW PATTERNS ABOUT SINGLE AND SUCCESSIVE BARRIERS

N. P. Woodruff and A. W. Zingg

Abstract--Atmospheric wind velocities were measured aft of a single and a series of three successive snow fences and compared to velocities measured aft of models of the fences placed in a wind tunnel. Results indicate the wind-tunnel approach gives a reasonable estimate of the effectiveness of full-scale surface barriers under atmospheric conditions. It is also shown that a series of three successive barriers is not enough to obtain a beneficial accumulative ground effect. A general lessening of velocity with distance traveled over the successive barriers indicates, however, that an accumulative effect might be obtained in a system containing a larger number of successive barriers extending for a great length. The barriers are shown to increase the velocity fluctuations of the wind from two to nine times at different locations aft of a single barrier. Maximum fluctuations in a series of successive barriers were found to occur at the 0.5-ft elevation aft of the second barrier.

Introduction--This study compares results from field and wind-tunnel investigations for one phase of the wind-erosion problem, namely, the use of artificial barriers. Field investigations of the wind-erosion problem and of methods for its control are perhaps the most obvious approach; they have, however, the disadvantages of high cost, dependence on weather, and inapplicability of the data to all regions. These disadvantages have led to the use of wind-tunnel methods. Qualitative evaluation of wind-tunnel data is a most perplexing problem. The primary objectives of this study were to determine: (a) whether the effect of surface barriers, such as windbreaks, on the atmospheric wind could be evaluated in a wind tunnel using models; (b) the accumulative effects on the air flow with successive barriers; (c) the effectiveness of barriers when approached by oblique winds; (d) the effects of single and successive barriers on the velocity fluctuations or eddies formed aft of each barrier; and (e) the effectiveness of the snow fence selected for this study.

Experimental equipment--The atmospheric wind study was conducted on an ungrazed Buffalograss pasture near Wakeeney, Kansas, in the Spring of 1953. The pasture had a uniform slope toward the south giving the wind an unobstructed approach for a distance of several miles. The roughness of the surface remained relatively constant throughout the study. Slat snow fence four feet high with a density of approximately 40 pct was attached to steel posts spaced 20 ft apart and placed on the location as shown in Figure 1. The orientation of the snow fence took advantage of the predominance of south-southwest winds. A 60-ft or 15-height spacing of the barriers was maintained throughout the experiment. A center stake position was used when measuring perpendicular winds. Positions to either side of the center line were for oblique winds.

The laboratory experiments were conducted in a wind tunnel described previously [ZINGG and CHEPIL, 1950]. The working section was a 16-ft length beginning 36 ft downwind from the fan. The floor of the tunnel was covered with sieved gravel, 1/6 to 1/4 inch in diameter. A turbulent boundary layer several inches deep was developed beyond the 36-ft point. Four galvanized tin model snow fences, each three feet long, were built on a scale of one inch equals one foot. These fences were placed in the tunnel singly and in groups of four. The spacing interval of 15 heights used for the atmospheric studies was maintained in the tunnel.

Velocities in the field were measured at 0.5, 1, 2, 4, and 6 ft above the ground elevation. All velocities except the unobstructed atmospheric wind were measured with Pitot tube-alcohol manometer combinations. The unobstructed wind was measured and recorded with Friez conical three-cup anemometers and a rebuilt triple register approximately 100 yards windward and away from the fence.

Procedure--Selected atmospheric winds with average velocities of 13.1 to 24.1 mph at the six-foot height were measured. Replicate velocity traverses were made aft of both the single and successive barriers under conditions of perpendicular and oblique wind directions. The unobstructed wind velocities were recorded simultaneously. In addition, 14 samples of open wind were taken with each Pitot tube-manometer combination over ten-minute periods to provide check data.

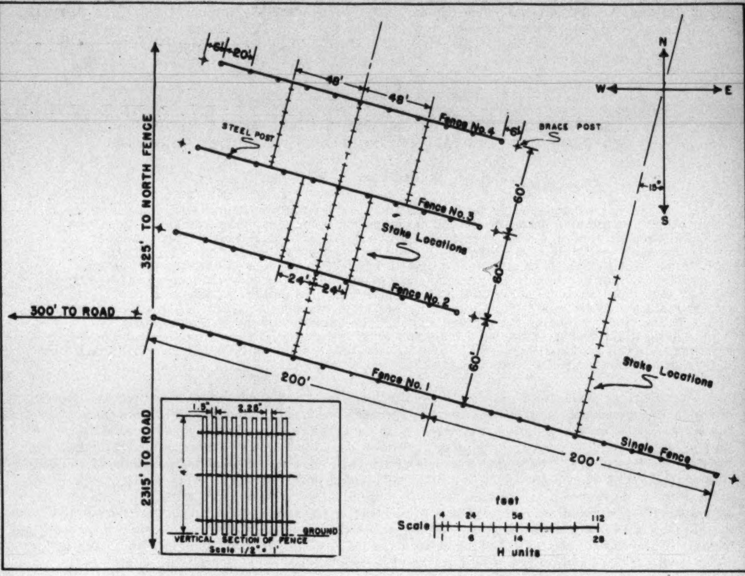
6'
20'
48'
48'
Fence No. 4
6'
BRACE POST
STEEL POST
Fence No. 3
Stake Locations
60'
60'
60'
24'
24'
Fence No. 2
300' TO ROAD
325' TO NORTH FENCE
2315' TO ROAD
200'
Fence No. 1
Single Fence
200'
Stake Locations
N
W
E
S
15°
1.5"
2.25"
4'
GROUND
VERTICAL SECTION OF FENCE
Scale 1/2" = 1'
feet
Scale
4
24
56
112
1
6
14
28
H units

Fig. 1--A map of the snow fence location used to study air-flow patterns

A complete velocity traverse consisted of taking instantaneous velocities at 30-sec intervals for ten-minute periods at 13 locations aft of the single fence and eight locations aft of each successive barrier. Three Pitot tube-manometer combinations were placed abreast at each station aft of the single fence. For successive barriers one instrument was placed at corresponding locations aft of fences 1, 2, and 3. All velocities were secured simultaneously and related to the corresponding ten-minute open-wind velocity.

Procedures for the wind-tunnel study were identical to those of the field with the exception that no oblique wind data were obtained, and velocities were measured at 12 vertical heights at 18 locations aft of the single fence. All tests in the tunnel were run in duplicate at wind speeds of 17.5 and 27.6 mph as measured in the center of the tunnel. These velocities were slightly higher than the 13.1- to 24.1-mph velocities existing for the atmospheric wind tests. Previous wind-tunnel studies of air-flow patterns about vertical plates [WOODRUFF and ZINGG, 1952] have shown, however, that the ratio of the velocity aft of the plate to the velocity at the same location in the clear tunnel is constant irrespective of the level of wind movement. The flow pattern in terms of this ratio, therefore, would not be affected by the magnitude of the velocities used.

Check data--Check data were obtained to determine whether operators, time lag, or some other variable could consistently cause one instrument to be read differently from another. The combined results of all check readings consistently show the following average ratio with respect to the anemometer: 1.017, 0.921, and 0.937 for instruments 1, 2, and 3, respectively. All data were adjusted, therefore, in accordance with these factors.

Effect of barriers on the air-flow pattern--The effects of the barriers on the air-flow pattern are shown in Figures 2, 3, and 4. These profiles were obtained by plotting the dimensionless ratios z/H and V_f/V_O, where

z = elevation above surfaces upon which barriers were placed
H = height of snow fence (four inches in model, four feet in prototype)
V_f = velocity aft of fence (V_f for atmosphere is ten-minute average)
V_o = velocity in open tunnel or unobstructed atmospheric wind

Vertical and horizontal distances on the profile maps are shown in terms of barrier heights H.

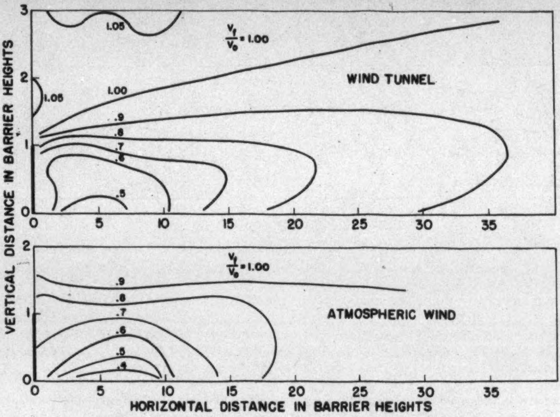

Fig. 2--Velocity ratios V_f/V_o obtained in vicinity of a single snow fence placed in the wind tunnel and in atmospheric winds

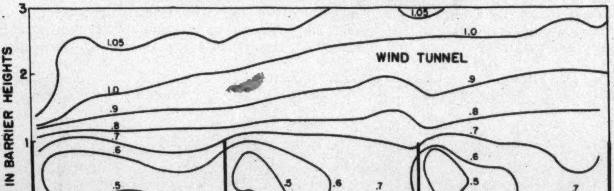

Fig. 3--Velocity ratios V_f/V_o obtained in vicinity of four successive snow fences placed in the wind tunnel and in atmospheric wind

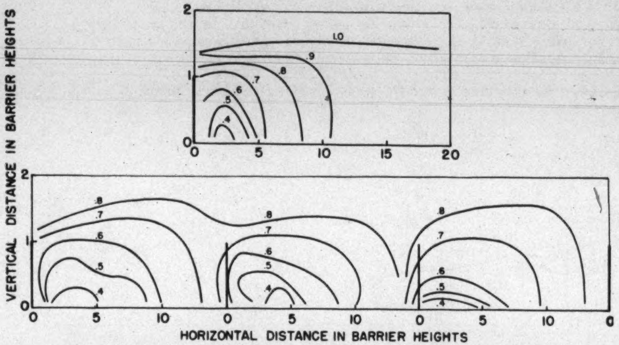

Fig. 4--Velocity ratios V_f/V_o obtained in vicinity of a single and four successive snow fences placed in oblique atmospheric winds

In general, the wind tunnel and atmospheric profiles are nearly the same behind both the single and successive barriers (Fig. 2 and 3). The extent of influence of the barriers at a height of 0.1 H is similar in the model and the prototype. The contour lines for the single fence are the averages of seven trials in the atmospheric wind and two trials in the wind tunnel. The successive fence profiles are averages of four field trials and two wind-tunnel trials.

The patterns in Figure 4 are for oblique winds aft of the single and successive barriers. They are averages of five southeast winds for the single fence and of one southeast and one northwest wind for the successive fences.

Effect of barriers on velocity fluctuations--The coefficient of variation $\sigma/\bar{u}$, where σ is the standard deviation of the instantaneous 30-sec velocities about the mean $\bar{u}$ for a ten-minute period, was used to gage the magnitude of the fluctuations. The curves of Figure 5 were obtained by plotting the quantity $\sigma/\bar{u}$ with respect to z, the height above the ground. Curves are shown for open wind and

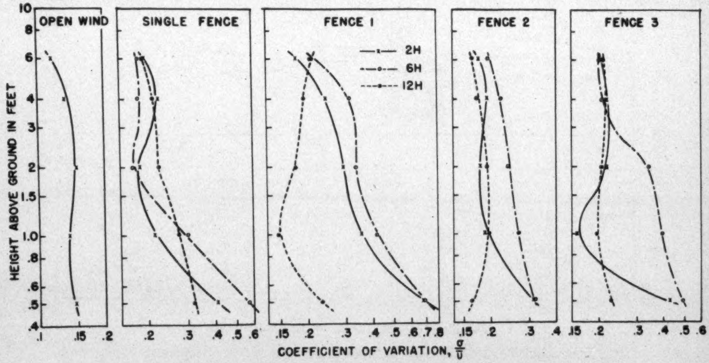

Fig. 5--A plot showing the coefficient of variation $\sigma/\bar{u}$ at various heights for open winds and for winds aft of single and successive snow fences for one wind from 10h 00m to 17h 25m on May 28, 1953

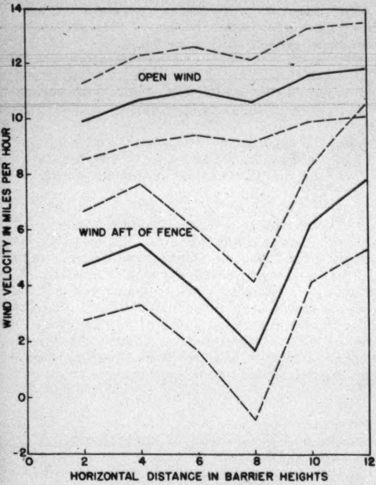

Fig. 6--A comparison of average, maximum, and minimum velocities at the 0.5-ft elevation for open wind and locations aft of a single snow fence; velocities used were obtained from 16h 25m to 17h 25m on May 28, 1953

for locations of 2 H, 6 H, and 12 H aft of the single and each successive barrier for one day of testing.

Average, maximum, and minimum velocities for both open wind and locations aft of the single barrier at the 0.5-ft elevation are shown in Figure 6. The maximum and minimum velocities were calculated from the velocity fluctuation data.

Discussion and conclusions--The results indicate that wind-tunnel approaches give reasonable estimates of the ground protection afforded by surface barriers under atmospheric conditions (Fig. 2 and 3). Statistical standard error of difference between means tests applied to tunnel ratios and to atmospheric ratios for both single and successive barriers showed no significant difference between means of the entire patterns in either case. This overall similarity of results between tunnel and atmosphere demonstrates rather close correspondence of behavior between model and prototype, even though the so-called 'model rules' were not strictly adhered to. Values of the Reynolds number, using the barrier height as the characteristic length, ranged from 48×10^4 to 88.2×10^4 for the atmospheric tests and from 5.3×10^4 to 8.4×10^4 for the tunnel tests. Previous studies using plates placed in a turbulent boundary layer [WOODRUFF and ZINGG, 1952] and artificially roughened pipes [ROUSE, 1938, pp. 241-244] have shown, however, that at this range of Reynolds numbers the drag coefficient becomes independent of the number, thus inferring similarity of flow patterns.

Interpretation of the results of the tests to determine possible accumulative effect from the use of successive barriers is dependent upon the vertical zone being considered. Results between the fences in the zone from the ground to the height of the barriers for both the tunnel and atmosphere actually indicate slightly more ground protection aft of the upwind barriers than aft of the downwind barriers. On the other hand, all the ratio lines above the barriers tend to rise in the interval extending from the first to last barrier (Fig. 3). This would indicate an adjustment toward a lower velocity above the fence with distance. A continuation of this trend over a larger number of successive fences would probably mean that the effect would extend down to the height interval between fences, thus giving an accumulative effect from use of successive barriers. In view of these results the following conclusions may be drawn: (1) Three or four successive barriers are not enough to create a beneficial accumulative surface effect on the air flow. (2) An accumulative effect for a system containing a larger number of successive barriers is indicated.

The results leading to the first conclusion are similar to those obtained by NÄGELI [1943] in making measurements over two sets of three successive shelter belts. He indicates a progressively lessened protection aft of the belts in a downwind direction for a set of young belts 5.5 m high. He also shows the third belt in a series of three older belts ten to 12 m high offers the least protection and the second gives the most protection. Previous studies of air flow about shelter belts or other barriers to the wind flow have not included a sufficient number of successive barriers to substantiate the second conclusion. It appears reasonable, however, when the fences are considered to be roughness elements of great magnitude affecting the wind flow as do smaller surface roughness elements, that is, the separation boundary is moved up an appreciable distance above the ground leaving a quieted zone in the roughness wake.

The results of the oblique-wind tests shown in Figure 4 indicate that the single barrier provides approximately one-half the protection obtained when the wind approaches the barrier perpendicularly. The protection from successive barriers is lessened by about two barrier-heights distance at all levels of the ratio for each fence. This lessened protection is apparently due not only to the wind passing around the ends of the barrier but also to the approximate ten per cent increase in fence density when winds strike the openings between slats at an angle.

Velocity fluctuations aft of the barriers are larger than those occurring in open winds (Fig. 5). Maximum velocity fluctuations for all the barriers tend to occur at 6 H. The greatest disturbance of the air flow occurs at the 0.5-ft elevation at 2 and 6 H aft of the first barrier.

Figure 6 indicates that an open wind having maximum fluctuations 14.6 pct greater than the average might have maximums ranging from 34 to 147 pct greater than average at different locations aft of a single fence. According to normal error these maximums and minimums should occur about 16 pct of the time.

The four-foot snow fence has been considered to be an experimental tool up to this point; however, it now seems appropriate to enumerate some of the protective features of this particular barrier. Apparently substantial reductions in average velocities for a single snow fence occur in a zone extending from approximately 16 to 40 ft. This, of course, is also a zone of increased velocity fluctuation. There is a reduction in wind velocity of at least 20 pct extending to a distance 80 ft aft of the single snow fence, and some influence is exerted to distances of 120 to 140 ft. The successive fence data indicate that the velocity will be reduced at least 30 pct aft of each fence with the 60-ft spacing used in this experiment. The use of successive fences causes the zones of maximum reduction to occur nearer to the second and third fences than the first. Judging from these results a spacing of about 40 ft, or 10 H, should give greater overall protection than the 60 ft, or 15 H, chosen for this experiment.

Acknowledgments--Grateful acknowledgment is made to the personnel of the U. S. Weather Bureau office at Topeka, Kansas, for their assistance in predicting winds; to Elmer Struss, the farmer on whose land the experiments were conducted; to G. W. Sidwell, the Trego county agent, for assistance in obtaining the location; and to C. S. Parsons, member of the project research staff, for assistance in taking data. This paper is Contribution 495, Department of Agronomy, Kansas Agricultural Experiment Station, Manhattan, Kansas, and Agricultural Research Service, Soil and Water Conservation Research Branch, Division of Soil Management - Irrigated and Dry Land Regions, U. S. Department of Agriculture, Cooperative Investigations in the Mechanics of Wind Erosion.

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CONVECTIVE HEAT TRANSFER WITH LIGHT WINDS

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Abstract--A simple expression for sensible heat flux under pure 'thermal' convection is developed on the basis of a fortunate observation of the shape and behavior of the individual convection cells. The cells of rising air were seen to be nearly circular in cross-section, the diameter decreasing upward, and separated from the environment by a sharp boundary in the lower levels. The model developed yields an expression involving only readily measurable parameters: height, mean temperature gradient, and difference of the modes of the instantaneous temperature frequency distribution.

Observations--The author, together with V. E. Suomi, has observed on the University of Wisconsin Marsh Farm a remarkably clear-cut and detailed example of convection under nearly calm conditions. The black peat soil was moist, the morning calm and cool, and the Sun bright in a cloudless sky. A thin sheet of steam was forming within a few inches of the soil, and every few meters in all directions this steam fog was rising in columns shaped like inverted funnels (see Fig. 1). The fog could be seen moving laterally to these columns, then rising at increasing speed. The rising air rotated rapidly both cyclonicly and anticyclonicly. No entrainment into these columns was apparent. In this case the regions of ascending motion were clearly these columns shaped like hyperbolic figures of revolution. They were sharp-edged to a height of about two meters above which mixing made them indistinct.

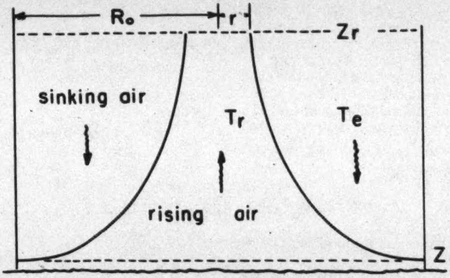

Fig. 1--Schematic vertical cross-section of a calm weather convective cell

The same phenomenon has been observed on Lake Mendota after cold outbreaks, the rising steam fog forming columns of apparently circular cross-section whose radius decreased with height.

Several observations mentioned by GEIGER [1950], especially those by RAMDAS and MALURKAR [1932], also indicate this particular form for the shape of the rising column of heated air.

Pertinent also to the question of the nature of these convection cells is the observation that, under such convective conditions, the frequency distribution of air temperature at low levels is bi-modal. There is a most frequent temperature, with random scatter on either side; but there is also another somewhat different frequent value with random scatter about it (Fig. 2). The separation of the two values may exceed 1°C.

We shall assume that the higher-valued temperature mode represents the cores of the rising convective columns and that the lower-valued mode is characteristic of the settling air, that is, the 'environment' temperature.

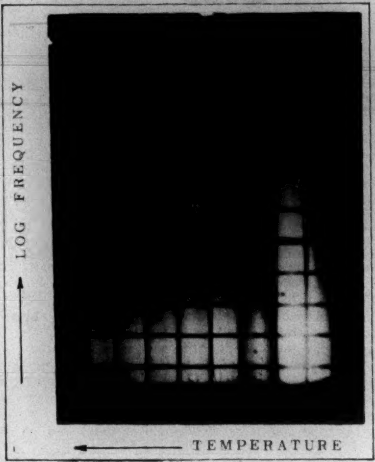

Fig. 2--Bi-modal gray-wedge frequency diagram of temperature at height of ten feet over University of Wisconsin Marsh Farm near noon on August 26, 1949; this temperature frequency diagram was made by taking ten-minute exposure of a DC oscilloscope tube viewed through a gray-wedge; the temperature, sensed with a thermopile, varied the vertical position of a horizontal sweep; the diagram has been rotated 90 degrees

Formulation--In addition to the assumption specified in the last paragraph, we shall assume that the acceleration of the rising air is purely buoyant, that the equation of mass continuity holds, and that the volume of the entire convection cell is sufficiently well approximated by a circular cylinder. No assumption is made about the nature of the process by which heat is transferred from the soil to the air except that it is confined to a rather shallow surface layer, say below the roughness height Z_o.

We shall take as the top of our convection cell the height Z_r at which the boundary of the rising air becomes turbulent and entrainment begins, that is, where the critical Reynolds number is exceeded. Below this height

$$dw_r/dt = g\,(T_r - T_e)/\bar{T} \cong g\Delta T/T \qquad \ldots\ldots\ldots (1)$$

where

w_r = upward velocity of the rising air
g = acceleration of gravity
T_r = temperature of the rising air
T_e = temperature of the environment

However

$$dw_r/dt = (dw_r/dZ)\,dZ/dt = -\,(w_r/A)\,dA/dt$$
$$= -\,(w_r^2/A)\,dA/dZ \qquad \ldots\ldots (2)$$

where

A = area of rising column = πr^2

Thus from (1) and (2) we obtain

$$-\,(2w_r^2/r)\,dr/dZ = g\Delta T/T \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

The equation of continuity for the cell may be written

$$\pi r^2 w_r = (\pi R_o^2 - \pi r^2)\,w_d \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where

R_o = radius of convection cell
w_d = downward velocity of environment

The net heat flux at a given level is

$$L = w_r \pi r^2 C_p \rho_r T_r - w_d\,(\pi R_o^2 - \pi r^2)\,C_p \rho_e T_e \qquad \ldots\ldots\ldots\ldots (5)$$

where

C_p = specific heat at constant pressure
ρ = density

Substituting (4) in (5)

$$L = w_r \pi r^2 C_p\,(\rho_r T_r - \rho_e T_e)$$

or if $\rho_r \sim \rho_e$

$$L \cong w_r \pi r^2 C_p \rho \Delta T \quad \ldots\ldots (6)$$

which gives, after squaring, solving for w_r^2 and substituting in (3)

$$(g\pi^2 C_p^2 \rho^2/2L^2)\ \Delta T^3/T = -\ r^{-5}\ dr/dZ \quad \ldots\ldots (7)$$

or integrating

$$r^{-4} - R_o^{-4} = (2g\pi^2 C_p^2\ \rho^2 \Delta T^3/L^2 T)\ Z = KZ \quad \ldots\ldots (8)$$

We shall now define the space mean temperature of the cell at a given height by

$$\overline{T}\pi R_o^2 = T_r \pi r^2 + T_e\ (\pi R_o^2 - \pi r^2) \quad \ldots\ldots (9)$$

whence the temperature gradient becomes, after substituting (7) and (8) in the height derivative of (9)

$$\partial \overline{T}/\partial Z = \Delta TK/2R_o^2\ (R_o^{-4} + KZ)^{-3/2} \quad \ldots\ldots (10)$$

Taking $R_o = 10^2$ to 10^3 cm, $\Delta T = 1°C$, $T = 300°K$, $Z = 100$ cm, and $L_o = 2 \times 10^{-3}$ cal/cm^2 sec, we see that R_o^{-4} is very much less than KZ and may be neglected. Thus if we let $L_o = L/\pi R_o^2$, that is, the heat flux per unit area, and solve (10) for L_o, we have

$$L_o = -\ 1.45\ (\Delta T/T)^{1/2}\ (\partial \overline{T}/\partial Z)\ Z^{3/2}\ \text{cal/cm}^2\ \text{min} \quad \ldots\ldots (11)$$

Verification--If the usual assumption is made that the heat flux is essentially constant with height, (11) gives the variation of lapse rate with height. Since ΔT does not vary with height within the limits we have chosen

$$\partial \overline{T}/\partial Z = \text{constant}\ Z^{-1.5}$$

This compares favorably with SUTTON's [1949, p. 27] empirical result

$$\Gamma + \partial \overline{T}/\partial Z = \text{constant}\ Z^{-1.75}$$

though this result is not supposed to be applicable below seven meters, while the development above should not apply above that level.

From the data of GERHARDT and GORDON [1948] for Gila Bend, Arizona, the mean temperature gradients for one light-wind case may be obtained by averaging the temperatures for each level, plotting a curve, and measuring tangents to the curve. Only for the heights below 12 inches does the minus three halves power approximate the observed values closely. This suggests that the height below which the mechanism described in this paper is presumed to operate, Z_r, is rather lower for this case than for the Marsh Farm case described in the first paragraphs above.

Another bit of information along these lines is contained in the data of Johnson and Best [GEIGER, 1950, p. 84]. The midday lapse rates for January and July over southern England at 0.025 to 1.2 m yield exponents of - 1.62, - 1.50, - 1.55, and - 1.95. The data of Malurkar and Ramdas [GEIGER, 1950, p. 60] yields a mean value between one and 13 cm of - 1.4.

It has been tacitly assumed in this discussion that the vertical gradient of the space mean of the temperature is equal to the time mean of the vertical temperature gradient. This will of course be true if the convection cells are not stationary and a sufficiently long average of the gradient is taken.

On May 28, 1952, from 10h 30m to 14h 30m CST, the sensible heat flux on the University Marsh Farm averaged 0.154 gm cal/cm^2 min. (Data for this example were collected by V. E. Suomi as part of GRD Contract No. AF19(122)-461.) During the same period the temperature distribution was clearly bi-modal. The average temperature of the environment during this time, measured at 33 cm was 0.89°C lower than that of the rising air, that is, $\Delta T = 0.89°C$. The air temperature was about 287°K, and the mean lapse rate 0.0135°C/cm. Wind data for early June indicate Z_o to be about six cm on the Farm. These figures give a computed sensible heat flux of 0.152 gm cal/cm^2 min. This is within two per cent of the observed value which, however, is probably not accurate to better than five per cent.

Acknowledgment--The author is indebted to V. E. Suomi for the data used in this paper and for helpful discussion of the problem.

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THERMAL RADIATION MEASUREMENTS IN SUMMER AND WINTER ALASKAN CLIMATES

Alice M. Stoll and James D. Hardy

Abstract--Thermal characteristics of the summer and winter Alaskan climates were evaluated by two methods: (1) direct measurement of solar and low-temperature radiation exchange by means of the panradiometer (an absolute radiation-measuring device described briefly) and by computation from the measured values, the mean radiant temperature of the environment; and (2) the direct measurement of the mean radiant temperature of the environment with the thermo-radiometer (which instrument and method of use is also described briefly) and by computation from these measurements, the solar contribution to the total radiation. During the summer period, the solar radiant flux occasionally exceeded 800 kg cal/m^2 hr. The mean radiant temperature of the environment varied from 8°C to 51°C undergoing large and sometimes rapid changes as the intensity of solar radiation varied with sky cover. During the winter period, the solar radiation attained only ten to 30 pct of the summer intensity. The mean radiant temperature varied from -3°C to -55°C and depended strongly on the radiant temperature of the sky, a concept introduced for simplification of the radiation-exchange problem. The latter temperature was greatly influenced by the water vapor content of the atmosphere.

Introduction--In the course of investigations undertaken to evaluate the radiant heat load on man in the outdoor environment, new instruments and methods were developed which may be of interest to meteorologists. It is the purpose of this communication to describe briefly two of these instruments and to present some of the data obtained with them in studies made recently in Alaska.

Instrumentation and methods--The panradiometer was used for the measurement of thermal radiation exchange and has been described in detail [RICHARDS, STOLL, and HARDY, 1951]. Briefly, it consists of three spheres, 6.5 mm in diameter, identical in construction but differing in emissivity. To produce this difference the surface of one sphere is painted black, another is painted white, and the third is highly polished. Each sphere is provided with a thermocouple for measuring its temperature and a high-resistance wire heater through which measurable amounts of heat may be supplied. Thus it is possible to determine the environmental thermal radiation exchange by virtue of the differences in emissivity both in the visible and in the infrared ranges simply by exposing all three spheres to the environment and measuring the quantity of heat supplied to each of two spheres to bring them to the temperature of the third. By repeating the procedure with the spheres shielded from direct sunlight, the sum of the energy reflected from the ground and the energy scattered by the atmosphere may be measured. Then from the measurements of total radiation and of reflected and scattered radiation, the intensity of the direct solar radiation may be calculated. From these data and the temperature of the spheres at equilibrium, the mean radiant temperature of the environment may be determined. A fourth sphere, highly polished, is provided for measurements of wind velocity after the manner of a hot-wire anemometer. A thermocouple, shielded from the sunlight, is provided for the measurement of air temperature (Fig. 1).

The second instrument used to obtain measurements discussed in this paper was a thermoradiometer which utilizes as radiation-sensing elements flake thermistors mounted behind a polished cone and connected to form a Wheatstone bridge [STOLL, 1954]. It was designed for use in ambient temperatures from -70°C to +70°C, covering the range of naturally occurring temperatures, for the measurement of the radiant temperature of the sky and of the ground, perhaps more properly called 'terrain' since it includes terrestrial objects as well as the Earth itself. This radiometer has been used in the field at ambient temperatures from -50°C to +55°C and is calibrated to measure radiant temperatures from -185°C to +100°C. The thermistor elements and their housing are shown in Figure 2. (The housing is approximately 3.5 cm in outside diameter and the thermistor elements are set back about three cm from the exposure aperture.) A detailed description of the instrument has been published [STOLL, 1954]. The method used for the determination of environmental radiant temperatures in the studies reported here is identical with that used previously [STOLL and HARDY, 1952]. Briefly, it consists of exposing the calibrated radiometer to the radiation from each of ten directions: zenith, and 45° above the horizon in the four cardinal compass directions, and nadir and 45° below the horizon in the four cardinal compass directions. A glass filter which screens out the infrared radiation was placed over the radiometer and the measurements repeated to provide corrections for scattered and reflected solar radiation during daylight hours.

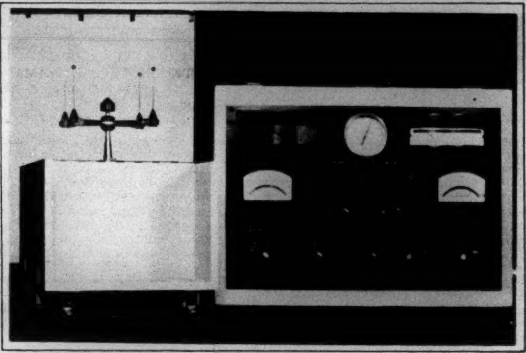

Fig. 1--Panradiometer measuring spheres and controls

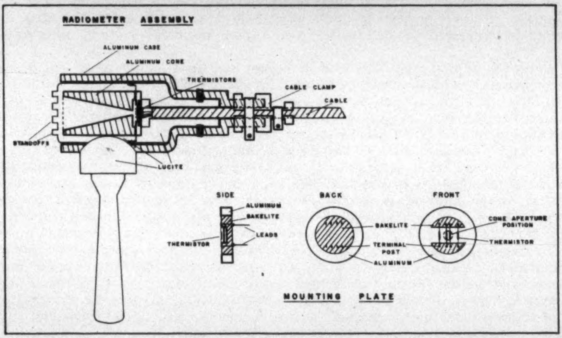
RADIOMETER ASSEMBLY
ALUMINUM CASE
ALUMINUM CONE
THERMISTORS
CABLE CLAMP
CABLE
STANDOFFS
LUCITE
SIDE
ALUMINUM
BAKELITE
LEADS
THERMISTOR
BACK
BAKELITE
TERMINAL POST
ALUMINUM
FRONT
CONE APERTURE POSITION
THERMISTOR
MOUNTING PLATE

Fig. 2--Thermistor radiometer sensing elements and housing

Measurement of solar radiation--Earlier attempts to compare panradiometer measurements of direct solar radiation made in Death Valley with weather station data obtained with the Eppley pyrheliometer (kindly supplied to us by Hans Neuberger of the Department of Meteorology, Pennsylvania State University) made on the same day at the nearest United States weather station indicated that no agreement could be obtained in this manner. Therefore, in the studies undertaken in Alaska direct comparisons were made with the panradiometer, the Eppley pyrheliometer mounted normal to the direct solar beam, and a surface radiometer such as that described by HARDY, WOLFF, and GOODELL [1952]. In Table 1 are shown some of these measurements made at Ladd Field, Fairbanks, on an especially clear day during August, 1952. Since measurements with the panradiometer entail a delicate heat balance and are made in two parts; that is, in sunshine and in shade, they are time consuming and it was possible to obtain only two measurements with this instrument during the time period indicated. The agreement among these three sets of measurements was within ±3 per cent.

Table 1--Radiometer comparisons, August 17, 1952

Time		Eppley pyrheliometer	Panradiometer	Surface radiometer
h	m	kg cal/m^2 hr	kg cal/m^2 hr	kg cal/m^2 hr
10	45	770	762	785
10	50	776	...	788
10	55	766	...	774
11	00	766	...	777
11	20	775	794	792
11	25	774	...	792

Measurements of the solar radiation were difficult to obtain with the panradiometer during the winter months because of the low intensity and diffuse character of this radiation. Some readings were made on rare clear days but for the most part reliance on the thermo-radiometer was necessary. Although this instrument was designed primarily to measure long-wave radiation, it was possible by use of a glass filter to obtain an estimate of the short-wave contribution of solar radiation. This was accomplished by making measurements with the glass filter in front of the radiometer, thus eliminating the long-wave radiation but allowing the short-wave radiation to pass through. Therefore, with the thermal radiometer directed toward the sky or the ground and taking into account filter absorption to the extent of five per cent, the scattered and reflected solar radiation could be determined. On clear days it was assumed that the deflections produced were proportional to the intensity of the direct solar radiation and the scattering coefficient of the sky and the reflecting power of the terrestrial environment. On completely overcast days in which the direct solar radiation could not be measured below the cloud layer, it was assumed this relationship is still valid. The readings obtained when the radiometer was pointed toward the sky and toward the ground are then respectively

$$D_3 = 0.95\gamma R_o \quad \ldots\ldots (1)$$

and

$$D_4 = 0.95\alpha R_o \quad \ldots\ldots (2)$$

then the solar contribution was

$$\gamma R_o + \alpha R_o = (D_3 + D_4)/0.95 \quad \ldots\ldots (3)$$

where D_3 = deflection on exposure to sky, D_4 = deflection on exposure to ground, R_o = direct solar radiation, γ = scattering coefficient, α = reflectivity coefficient, $(\alpha + \gamma) R_o$ = indirect solar radiation, and 0.95 = correction factor for filter absorption.

The thermo-radiometer is calibrated with a Leslie cube directly in terms of temperature difference between a radiating black body source and a standard black body [STOLL and HARDY, 1952], thus all deflections are automatically and correctly expressed in temperature difference. This is true as long as the emissivity of the radiometer does not alter within the spectral range of the measured radiation, namely, 0.4 - 40μ. The nature of the construction of the radiometer permits this assumption to be made safely. It is therefore valid to consider any deflections as being caused by radiation from a black body at some temperature. Thus, for the purpose of computing the energy involved, the deflections produced by the scattered and reflected solar radiation may be considered as being due to radiation from a fictitious black body capable of giving the actual deflections D_3 and D_4. These equations may be written as

$$D_3 = S_o (T_3^4 - T_r^4) \quad \ldots\ldots (4)$$

where T_3 = equivalent low temperature radiant temperature of the sky, S_o = Stefan-Boltzmann constant, and T_r = temperature of the reference black body.

and

$$D_4 = S_o (T_4^4 - T_r^4) \quad \ldots\ldots (5)$$

where T_4 = equivalent low temperature radiant temperature of the terrain.

Then for clear days, provided that exposure to direct solar radiation is avoided, reflection plus scattering may be measured as

$$\alpha R_o + \gamma R_o = [S_o (T_3^4 - T_r^4) + S_o (T_4^4 - T_r^4)]/0.95 \quad \ldots\ldots\ldots\ldots\ldots (6)$$

and on completely overcast days when all of the solar contribution is composed of scattered and reflected radiation, this is also the total solar radiation contribution, R_o. A test of this formula is possible by making simultaneous readings with the panradiometer and thermo-radiometer. Although this was rarely possible during the winter observations, the results of two attempts are shown in Table 2, and a rough approximation was made from the data obtained during clear and partly clear days of August, 1952. Since the summer observations were not made with this purpose in mind, they were not taken with the two instruments simultaneously, but were within a half-hour of each other and at approximately the same locations. A plot of these values is shown in Figure 3, where $(D_3 + D_4)/0.95$, expressed in kg cal/m^2 hr, is shown on the ordinate; and the scattered and reflected radiation measured with the panradiometer is shown on the abscissa. Although the scatter of points is obviously large, the agreement is as good as can be expected of measurements made at somewhat different times. Figure 4 is illustrative of the effect of relatively small differences in the time of measurement, as well as of the difference in the functional principle of each of these instruments. Thus, it is seen that in a sequence of measurements of reflected and scattered energy the thermo-radiometer measurements show less variation than the panradiometer, although both follow the same general trend with the conspicuous exception of the measurements made at 10h 45m and 10h 50m. This feature is due to the fact that each thermo-radiometer value is derived from ten observations, five of the upper hemisphere and five of the lower hemisphere, whereas each panradiometer value is obtained from a single measurement taken at the moment of heat balance among the different spheres. Differences in the shape of the radiation receptors do not contribute to discrepancies between comparable values obtained with the two instruments since shape is taken into account in the computations [RICHARDS, STOLL, and HARDY, 1951]. Thus, the former measurement represents an average reading over a period of about one minute while the latter describes the thermal exchange existing at the moment of balance and is extremely sensitive to transient influences such as cloud movement with respect to the Sun, as well as rapidly varying air velocity such as exists during gusty weather. During the measurements presented here, the air currents were not uneven and offered no difficulties, but a huge cloud mass traveling rapidly, crossed the sky, passing over the face of the Sun from about 09h 30m to 11h 30m, and disappeared under the horizon about 13h 30m. The magnitude of the cloud mass may be appreciated from the estimate of total sky coverage recorded by the CAA weather station where the radiometers were located (stippled block). (The authors are most grateful to the personnel at this station for their permission to set up instruments on their observation platform and for their

Table 2--Total radiation (R) and scattered + reflected solar radiation ($\alpha R_o + \gamma R_o$) measurements

Date	Time (Alaska standard)	Panradiometer kg cal/m^2 hr			Thermo-radiometer kg cal/m^2 hr
		R	R_o	$(\alpha + \gamma) R_o$	$(\alpha + \gamma) R_o$
January 27, 1953	1035	34.0	0	(34.0)[a]	39.6
February 4, 1953	1100	111.2	236	47.6	40.2

[a] No change when shielded from direction of the Sun, therefore reflected and scattered radiation = total radiation.

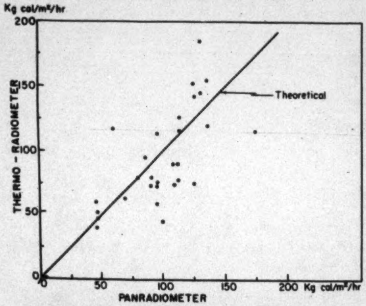

Fig. 3--Comparison of measured values of reflected and scattered solar radiation obtained with the thermo-radiometer (ordinate) and with the panradiometer (abscissa)

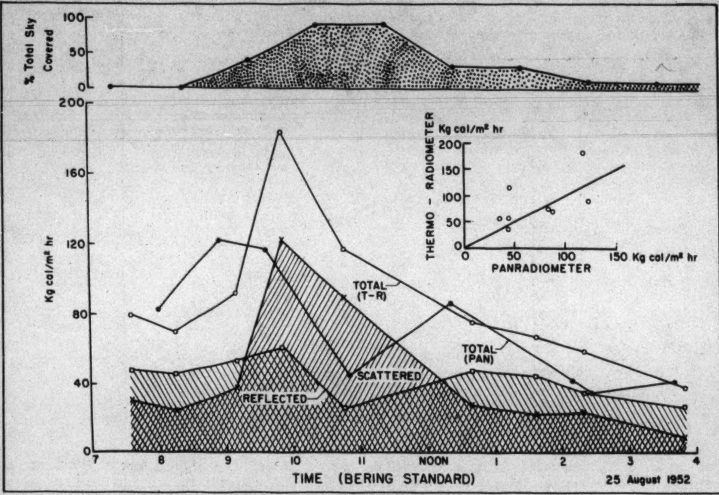

Fig. 4--Comparison of panradiometer and thermo-radiometer measurements of reflected and scattered solar radiation

fine cooperation in making their official records of weather data available to us.) The effect on the comparison of the two radiometers produced by such rapidly varying radiation conditions is most apparent in the measurements at 09h 35m (panradiometer) and 09h 50m (thermo-radiometer). An apparent discrepancy of about 70 kg cal/m^2 hr exists when plotted as simultaneous readings (Fig. 4, inset - highest point on ordinate; solid line represents theoretical points of perfect agreement) but when plotted against time (main curves - P-R 09h 35m, T-R 09h 50m), it is seen that the panradiometer value lies almost on the curve of the thermo-radiometer value. It is further obvious from the separate measurements of reflection (hatched, slanting up left) and scattering (hatched, slanting up right) that under these conditions the panradiometer measurements were more influenced by reflected than by scattered energy although under more stable conditions (12h 00m to 16h 00m) the agreement between the two types of measurements is quite good even in the presence of strong direct solar radiation.

Measurement of the mean radiant temperature of the sky and terrain--As previously defined [STOLL and HARDY, 1952], the 'radiant temperature' of a source of thermal radiation is the temperature of a fictitious black body emitting energy at the same rate as the source. Thus, although the actual radiating source may be of unknown emissivity and absolute temperature, its rate of emission can be set equal to the emission of a black body at some temperature, that is, the 'radiant temperature.' From radiometric measurements of the sky, it is not possible to say precisely which cloud masses are radiating or what their actual temperature is, but it is possible to locate sinks and sources of radiation and to evaluate them in terms of low-temperature radiation exchange. Similar considerations apply to measurements of the radiant temperature of the terrain. These measurements were made with the thermo-radiometer. The deflections obtained on exposure of the radiometer without the filter resulted from the low-temperature radiation and the solar radiation. Thus $D_1 = S_o\ (T_1^4 - T_r^4) + \gamma R_o$ for the sky, and $D_2 = S_o\ (T_2^4 - T_r^4) + \alpha R_o$ for the terrain. The necessity for taking into account the scattered and reflected solar radiation as measured with the glass filter in place is seen from Figure 5 in which are plotted the low-temperature radiant temperatures of the sky and of the ground with the sunlight included (uncorrected) and with the sunlight eliminated by correcting for the scattered and reflected solar radiation. The influence of the sunlight upon the sky, and snow low-temperature radiation measurement is small (corrected curves), but when the corrections for reflected and scattered solar radiation are not applied, as in the uncorrected curves, an apparent drop of more than 30°C in the low-temperature radiant temperature of the snow and sky occurred as the Sun disappeared between 14h 00m and 16h 00m.

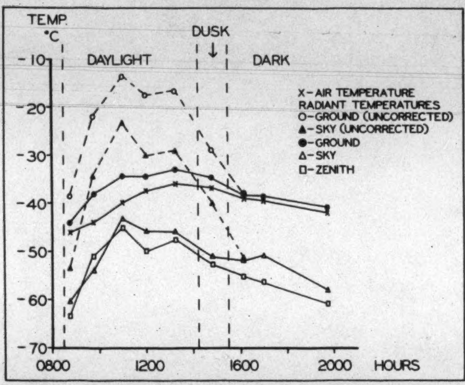

Fig. 5--Effect of scattered and reflected solar radiation on measurement of radiant temperatures of sky and ground, February 5, 1953

Results--The detailed observations with the panradiometer made during August, 1952, at Fairbanks and at Nome, Alaska, are shown in Tables 3 and 4. Most of the material is self-explanatory, however, under the heading 'Radiation intensity kg cal/m^2 hr' the quantities shown were determined specifically for the purpose of obtaining the total radiation effective on man at the Earth's surface and are related in the following manner

$$R = R_0 + (\alpha + \gamma) R_0 \pm H_t \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

where R = total radiation incident on man; R_0 = direct solar radiation, incident normal to the direct solar beam, exclusive of indirect, or scattered and reflected solar radiation; $(\alpha + \gamma) R_0$ = the sum of reflected plus scattered solar radiation, exclusive of direct solar radiation; and H_t = gain or loss by low-temperature radiation exchange with warm or cold surroundings.

The extraction and application of these data is the subject of a previous publication [RICHARDS, STOLL, and HARDY, 1951], therefore, only the general equation is presented here. Although the data apply strictly only to spherical bodies, by simple transformations they can be made applicable to any object of known shape on the Earth's surface, at the site of measurement.

Because of the very low intensity of the solar radiation on most of the winter days, the panradiometer could not be used effectively during January and February of 1953.

The observations with the thermo-radiometer were made both in the summer and winter months and these results are summarized in Tables 5 and 6. In Table 5, only the long-wave radiation data are given after conversion into radiant temperature (equivalent black body temperature) of sky and terrain. In Table 6 are included the averages of the actual readings without the filter and through the glass filter. The latter readings when used in (6) were frequently sufficient to measure R_0, the solar radiation, because of the low intensity and diffuse character of this radiation in the winter.

Discussion of summer observations--In spite of the low altitude of the Sun in Alaska, a comparison of maximum solar radiation intensity as measured in New York City and in Death Valley [STOLL, 1951] indicates that some of the highest intensities were actually measured in Alaska. The comparison given in Table 7 is believed valid as the highest values measured during summer experiments were used, although the New York data were taken in June rather than August when higher values might be expected to occur. Indeed, somewhat higher values could undoubtedly be found in all three localities in a more extensive series of studies.

High solar-radiation intensity is usually associated with quite clear skies, and clear skies provide a strong sink for low-temperature radiation. This is shown particularly well in the data

Table 3--Panradiometer data, Fairbanks

Date	Time (Alaska standard)	Radiation intensity, kg cal/m^2 hr			Average radiant temperature of sky and terrain	Air temperature	Wind velocity
		Solar (normal to plane)	Reflected and scattered	Total			
1952					°C	°C	ft/min
August 4	1500	595	113	223	20.9	28.9	245
August 4	1950	0	0	38	17.6	20.0	255
August 5	1010	685	158	355	19.2	23.7	589
August 5	2030	0	0	4	7.5	19.8	235
August 6	1430	644	157	334	22.6	27.3	549
August 6	1640	563	43	188	18.2	27.2	792
August 6	1920	0	0	19	12.0	21.9	792
August 7	0830	0	0	23	15.1	18.9	792
August 9	0745	631	86	252	11.0	18.1	254
August 9	0845	682	86	265	8.2	22.2	792
August 9	0930	544	124	272	16.4	22.0	333
August 11	0910	68	98	125	10.1	15.6	1960
August 15	0850	0	0	127	9.1	10.1	1177
August 15	1710	0	0	53	8.8	12.2	529
August 17	1000	572	118	273	7.2	18.9	412
August 17	1045	762	89	288	6.7	18.3	792
August 17	1120	794	103	311	9.2	20.3	941
August 18	0945	445	109	248	12.3	17.8	432
August 18	1310	445	155	177	16.0	19.2	1520
August 19	0815	0	0	123	17.0	13.7	588
August 19	1050	536	102	246	14.0	19.2	1039
August 19	1317	737	114	309	15.8	22.8	1096
August 19	1540	496	91	224	13.0	21.8	862
August 19	1705	216	63	138	12.6	21.7	1039
August 20	1100	728	113	306	13.3	20.0	882
August 21	0907	663	78	251	5.6	15.4	921
August 21	1035	53	99	122	9.6	15.6	529
August 22	1342	672	104	282	11.0	15.3	922
August 28	1005	783	83	287	3.5	16.3	490
August 28	1100	791	72	277	8.8	19.1	392

taken on August 25, 1952, at Nome. As noted previously, the day was a particularly clear one with large cumulus clouds appearing for a relatively short time. In Figure 6 the reciprocal relationship of radiant sky temperature to R_0, the direct solar radiation, is pointed out strikingly; as the cloud cover moved in, R_0 diminished precipitously and the radiant sky temperature (corrected for scattering) rose 26°C and then fell 15°C as the skies cleared. The radiant temperature of the ground (corrected for reflection), on the other hand, was strongly influenced by the Sun, increasing as the solar-radiation intensity increased. Furthermore, when the sky was obscured by the clouds, loss of heat by radiation was blocked and the radiant temperature of the ground actually increased temporarily while the air temperature remained fairly constant throughout.

It has been noted that when there are thick clouds or heavy overcast, the sky and terrain equivalent black body radiant temperature, exclusive of short-wave radiation, and the air temperatures tend to be equal and a roughly linear relationship can be shown between the clearness of the sky and the decrease in radiant temperature difference between Earth and sky [STOLL and HARDY, 1952]. Angstrom, ELSASSER [1942], Wexler, HAURWITZ [1951], and others have made calculations of this heat loss. With the radiometer, the measurements can be made directly and show agreement with the general idea that the loss of heat by radiation is largely dependent upon visible water (clouds) and invisible water vapor in the air. Thus, the dryer the air, such as on clear days in Fairbanks, the 'colder' will be the sky. In Figure 7 is shown a plot of upper atmosphere temperatures measured by radiosonde during a Fairbanks summer. At the bottom of the chart is shown by

Table 4--Panradiometer data, Nome

Date	Time (Bering standard)	Radiation intensity, kg cal/m^2 hr			Average radiant temperature of sky and terrain	Air temperature	Wind velocity
		Solar (normal to plane)	Reflected and scattered	Total			
1952					°C	°C	ft/min
August 25	0800	629	83	248	4.5	14.4	509
August 25	0855	648	123	297	1.0	14.0	688
August 25	0935	52	117	142	6.9	14.5	688
August 25	1050	245	45	122	7.7	12.8	804
August 25	1220	737	87	245	11.3	14.6	1186
August 25	1410	778	43	242	8.8	13.9	706
August 25	1425	817	35	243	6.9	14.7	706
August 25	1540	814	43	250	7.1	13.9	688
August 25	1750	424	67	180	2.4	13.9	686
August 26	0700	649	114	287	3.9	11.0	509
August 26	0755	794	43	246	6.8	17.2	509
August 26	1330	616	86	248	8.1	15.6	549
August 27	0925	830	78	292	3.9	15.0	882
August 27	1035	356	86	184	6.1	15.4	725

Table 5--Thermo-radiometer data in summer

Hemisphere	Average radiant temperatures			
	Fairbanks (32 observations)		Nome (23 observations)	
	Temperature	Range	Temperature	Range
	°C	°C	°C	°C
Upper (sky)				
Zenith	4.9	-13.2 to +22.4	-3.2	-17.5 to +16.6
North	6.1	-11.2 to +19.9	0	-13.6 to +11.5
East	7.8	- 9.4 to +19.9	0	-15.1 to +27.7
South	8.3	-10.1 to +22.0	+2.3	-12.5 to +11.6
West	6.9	- 9.6 to +30.4	+0.1	-14.6 to +12.4
Average sky	7.0	- 9.5 to +20.8	-0.1	-14.2 to +14.8
Lower (terrain)				
Nadir	20.1	+ 9.7 to +33.9	13.2	- 6.5 to +20.9
North	21.1	+ 6.7 to +31.3	13.5	- 4.6 to +28.5
East	23.5	+ 8.7 to +33.2	13.8	- 5.2 to +23.7
South	22.9	+ 6.7 to +35.3	13.6	- 3.7 to +28.5
West	21.7	+ 6.7 to +32.5	12.7	- 2.7 to +26.4
Average terrain	21.9	+ 7.5 to +30.8	13.3	- 3.4 to +21.9

the cross-hatched columns a distribution of the summer radiant sky temperatures, exclusive of solar radiation, as measured at the zenith. From the figure it is seen that the radiant temperature at the zenith corresponds to air temperatures from zero altitude to roughly 10,000 ft. Unfortunately, data on moisture content of the upper air were not available for the summer readings.

Discussion of winter observations--The solar radiation in Fairbanks during January and February amounted to only about ten to 30 pct of the highest observed summer values on the few days when it could be measured with the panradiometer. Thus, while the Sun makes an appreciable contribution to the radiant temperature on the winter day, that is, an elevation of six to 15°C, its effect is not dominant.

-Table 6--Thermo-radiometer data, Fairbanks in winter

Hemisphere	No solar radiation (night) T_r °C Average -33°.2, Range -45 to -5.5°			Solar radiation present T_r °C Average -26°.7, Range -46.0 to 0°			
	Number of observations	No filter required, deflections	Average radiant temperature	Number of observations	No filter deflections	Filter deflections	Average radiant temperature
		°C	°C		°C	°C	°C
Upper (sky)							
Zenith	53	-15.2	-48.4	91	-5.8	+6.8	-39.3
North	53	-13.1	-46.3	91	-2.7	+8.3	-37.7
East	53	-12.0	-45.2	91	-0.3	+9.4	-36.4
South	53	-11.2	-44.4	69[a]	+4.1	+12.9	-35.5
West	53	- 9.8	-43.0	85[a]	+1.0	+9.0	-34.7
Average sky	...	-12.3	-45.5	...	-0.7	+9.3	-36.7
Range of average	...	-42.4 to +8.7	-69.4 to -7.1	...	-25.7 to +27.5	+0.6 to +28.6	-64.5 to -2.8
Lower (terrain)							
Nadir	53	+ 0.7	-32.5	91	+5.2	+6.5	-28.0
North	53	- 1.1	-34.3	91	+6.6	+8.3	-28.4
East	53	- 1.3	-34.5	91	+6.9	+8.4	-28.2
South	53	+ 0.2	-33.0	88[a]	+5.5	+6.8	-28.0
West	53	0	-33.2	91	+6.8	+7.4	-27.3
Average terrain	...	- 0.3	-33.5	...	+6.2	+7.5	-28.0
Range of average	...	-12.4 to +6.9	-43.0 to -9.5	...	-10.9 to +31.6	0 to +25.6	-45.6 to -4.5

[a] Readings off-scale omitted.

T_r = reference temperature (equivalent to ambient temperature); radiant temperature (no filter required) = (deflection °C + T_r °C); radiant temperature when the filter was used = [(deflection without filter °C - deflection with filter °C) + T_r °C].

Table 7--Intensities of solar radiant flux (R_o) normal to plane

Death Valley (Furnace Creek) (August)	Nome (August)	Fairbanks (August)	New York City (June)
956	830	794	729
843	817	719	703
795	814	783	653

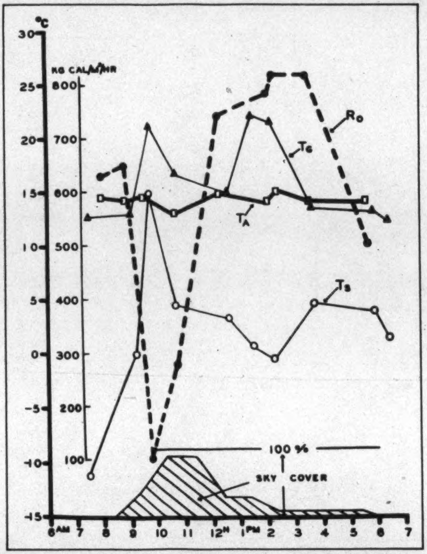

Fig. 6--Variation in solar radiation and environmental temperature, August 25, 1952, Nome, Alaska; R_o = direct solar radiation, T_g = radiant temperature of ground, T_a = air temperature, T_s = radiant temperature of sky, and sky cover = pct of total sky covered by clouds

It is seen in Figure 7 that some of the radiant sky temperatures in the winter (clear columns) were lower than the temperature of any air mass intervening. In Figure 8 are shown data taken January 23-24, 1953, which illustrate some of the observed winter phenomena. The first two measurements shown were made through the ice fog, and the succeeding observations were made from the Geophysical Observatory of the University of Alaska situated on a hilltop above the ice fog. Sunset occurred about 15h 00m on this day.

The difference between the first two readings and the next four indicated that the radiant temperatures were about 4°C higher under the ice fog than above it. As will be seen presently, ice fog has little effect in preventing the escape of radiation from the Earth to the sky. Thus, the higher temperature under the ice fog must be attributed to the effect of scattered solar radiation which was of relatively low intensity, about 50-60 kg cal/m^2 hr, under the ice fog.

The subsequent measurements on this day show the striking effect of moisture in screening out the strong sink which a clear sky forms for radiation. Thus, with clouding over of the sky prior to

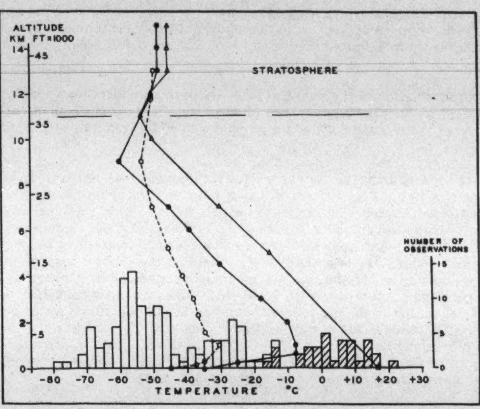

Fig. 7--Radiosonde air temperatures compared with radiant sky temperatures measured at the zenith; the solid line through open triangles represents an average of summer readings; the solid line on closed circles represents the highest temperature, and the broken line on open circles, the lowest temperature recorded during the winter experiments; the clear columns represent number of observations in winter and the hatched columns, the number in summer

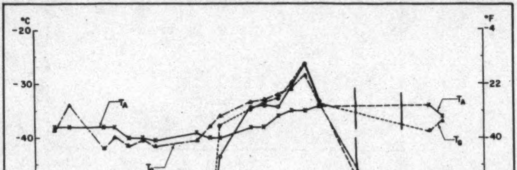

Fig. 8--Effect of fog and snow on environmental radiant temperatures; T_a = air temperature, T_g = radiant temperature of ground; T_s = radiant temperature of the sky, and T_z = radiant temperature of the sky at the zenith

the precipitation of snow, the radiant sky temperature rose almost 25°C approaching the radiant snow temperature and becoming warmer than the air. This marked change in the thermal environment was followed several hours later by an increase of 5°C in the air temperature. This lag in the change of air temperature is noticed on most occasions when marked rapid alterations in radiant temperature were observed. The thermal lag in radiant temperature of the snow was generally short which may be attributed to the fact that snow radiates almost like a black body in the infrared.

Following the cessation of the snowfall, the sky became quite clear and during the following two days the lowest sky temperatures were measured. The lowest value of radiant sky temperature observed during this series of measurements was -76°C (197°K) at 21h 00m on January 24, 1953.

Certainly, the low radiant temperature on occasions of clear sky in the winter as compared with summer readings (see Fig. 7) indicates that the radiation from the radiometer is comparatively unimpeded in the winter. The importance of water vapor in this respect is shown quantitatively in Figure 9 where the radiosonde data are plotted against the radiant sky temperature for the corresponding times. Extrapolation to zero water vapor, neglecting the weaker absorbers, yields a minimum temperature of about 200°K. Thus, as the vapor pressure of water falls because of cooling during the winter months, the sky becomes progressively clearer as regards the infrared radiation from the Earth (spectral range 6 - 40μ). This promotes enhanced cooling of the snow surface as well as cooling of the air masses near the Earth containing water vapor. Further condensation and precipitation of water results thereby making the sky even 'colder,' and the cooled air mass sinks displacing warmer air. The cooling of the air and the snow by radiation to the cold sky operates to make the air close to Earth (and undisturbed by winds), exceptionally cold, contributing to the sharp temperature inversions as shown in Figure 7.

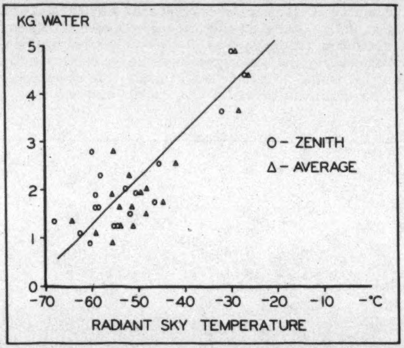

Fig. 9--Atmospheric water vapor content in kilograms of water in a column of air one meter square at the base and seven kilometers in altitude plotted against corresponding radiant sky temperatures

The ice fog apparently contributes to this cycle because the fog, in contrast to clouds, is almost transparent to the thermal radiation from the snow whereas similarly to clouds it is almost opaque to solar radiation. On two occasions measurements of radiant sky temperature were made at Ladd Field through dense ice fog and immediately afterward at a higher location where there was no fog. The results are shown in Table 8. The actual water vapor content of the ice fog is judged to be small although the ice crystals form a good reflecting layer for the sunlight. Overcast, on the other hand, is opaque to the radiation from the Earth. In a limited degree the ice fog serves as a reverse 'greenhouse' layer.

An additional phenomenon is the marked alterations in radiant temperature which may occur rapidly and not be manifested in either a change in air temperature or wind velocity. Such changes may be associated in the summer with changing solar radiation (Fig. 6) and in the winter, occasionally with snowing (Fig. 10). In the instances shown here, the precipitation of snow from cooler air layers lying above warmer and more moist layers caused a temporary clearing of the sky (lowering sky temperature) and a lowering of the terrain temperature with a covering of cold snow.

Table 8--Influence of ice fog on radiant sky temperature (zenith measurements)

Ladd Field ice fog	Steele Creek Road no fog	Ladd Field overcast
°C	°C	°C
-49	-51	-38
-52	-55	-40
-58	-60	-34
-57	-57	-35
-58	-57	-40

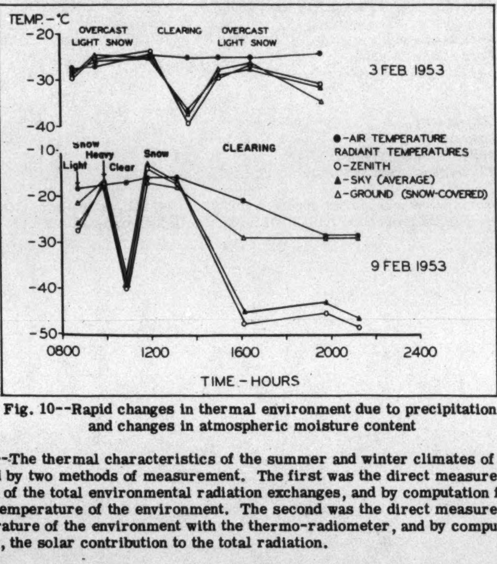

Fig. 10--Rapid changes in thermal environment due to precipitation and changes in atmospheric moisture content

Summary--The thermal characteristics of the summer and winter climates of interior Alaska were evaluated by two methods of measurement. The first was the direct measurement with the panradiometer of the total environmental radiation exchanges, and by computation from these, the mean radiant temperature of the environment. The second was the direct measurement of the mean radiant temperature of the environment with the thermo-radiometer, and by computation from these measurements, the solar contribution to the total radiation.

During the summer period, the solar radiant flux measured normal to the direct solar beam was frequently as intense as it is in the desert region at Death Valley, occasionally exceeding 800 kg cal/m^2 hr. The summer mean radiant temperature of the environment varied from eight to 51°C undergoing large and sometimes rapid changes as the intensity of solar radiation varied with changes in sky cover. Intense solar radiation was usually accompanied by clear skies which afforded a strong sink for low-temperature radiation. Conversely, weak solar radiation was accompanied by overcast skies which blocked low-temperature radiation losses.

During the winter period, the solar radiation attained only about ten to 30 pct of the summer intensity. The mean radiant temperature varied from -3 to -55°C and depended strongly on the radiant temperature of the sky. The sky temperature, in turn, was greatly influenced by the water vapor content of the atmosphere which was frequently so low as to allow appreciable low-temperature radiation from the Earth's surface to escape to outer space.

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SILVER IODIDE CLOUD SEEDING IN PUERTO RICO

Leo Alpert

Abstract--The results of field work in Puerto Rico in November, 1953, as a consultant for the Puerto Rico Water Resources Authority to investigate the possibilities of stimulating rainfall through cloud seeding with silver iodide ground generators are reviewed. Few opportunities for cloud seeding with silver iodide ground generators were observed. Most often rain fell from warm cumulus clouds with tops between 8000 and 12,000 ft, far below the -5°C level between 17,000 and 18,000 ft where silver iodide first becomes effective as a nucleating agent. Few cumulus grow to the -5°C level between 17,000 and 18,000 ft. Those that were observed to grow to the -5°C level where silver iodide crystals might be effective started to give rain when the tops were between 8000 and 12,000 ft, and those clouds usually yielded such intense showers that seeding to increase the fall might result in destructive erosion and floods. An analysis of the meteorological records for the dry season indicates that the trade inversion would form an effective ceiling to the penetration of the silver iodide smoke aloft.

Introduction--In November, 1953, the Puerto Rico Water Resources Authority invited the writer to visit Puerto Rico as a meteorological consultant to investigate the possibilities of increasing the rainfall of the Island by cloud seeding. Although the investigation included all aspects of cloud seeding, this article is limited to an evaluation of the possibilities of cloud seeding with silver iodide ground generators.

Puerto Rico has a tropical marine climate largely due to its location at latitude 18°N in the eastern part of the Caribbean Sea. It is a small island, about 95 by 35 mi (see Fig. 1). Its area is smaller than that of the State of Connecticut.

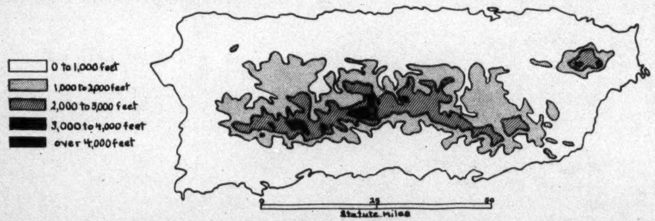

Fig. 1--Topographic map of Puerto Rico

The central mountain backbone with peaks exceeding 3500 ft forms a more or less continuous divide in an east-west direction ten to twelve miles from the south coast. The mountains produce a surprising diversity in the areal distribution of rainfall (see Fig. 2) [PICÓ, 1950]. The mean annual rainfall ranges from less than 25 inches on the semiarid southwestern coast to more than 200 inches on some windward mountain slopes.

Rainfall exhibits a marked seasonal variation as well as areal variation. For most of the Island, summer and autumn (Table 1) are the rainy season, and winter and early spring (December through March and in some years continuing through July) are the dry season. Showers yield some rainfall over some part of the Island virtually every day in the year. Probably February is the only month of the year having occasional periods of three or four days without some rain falling somewhere within the Island.

The 60 inches of rain which falls in normal years on the eastern part of the north coast is barely sufficient for the growth of sugar cane without irrigation. Droughts occur locally from time

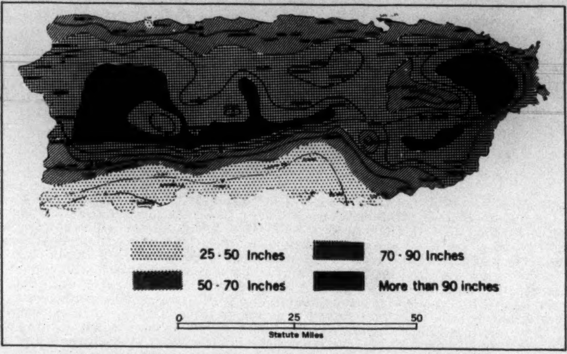

Fig. 2--Mean annual rainfall map of Puerto Rico

Table 1--Rainfall in inches at three stations in Puerto Rico

Item	Year		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
	From	To													
Fajardo (40 ft above sea level)															
Minimum	1898	1953	0.85	0.10	0.53	0.71	1.69	1.10	1.32	1.64	2.38	2.75	1.55	1.20	....
Mean	1898	1950	3.55	2.89	2.80	3.78	6.73	5.47	5.55	6.17	7.50	8.35	7.72	4.51	65.02
Maximum	1898	1953	11.56	9.87	5.81	13.77	19.29	16.29	16.10	16.02	15.68	19.58	15.34	14.54	....
	1953		1.45	0.84	5.81	1.69	5.82	4.37	6.87	4.47	5.12	6.40	5.73	3.85	52.42
San Juan (47 ft above sea level)															
Minimum	1899	1953	1.26	0.05	0.34	0.42	0.71	1.43	1.10	1.53	1.49	1.61	1.63	0.98	....
Mean	1899	1953	4.36	2.63	2.60	4.01	6.06	5.34	6.08	6.15	6.13	5.47	6.68	5.23	60.74
Maximum	1899	1953	15.47	7.84	9.38	13.17	16.88	12.22	10.98	14.10	13.68	12.15	15.64	15.40	....
Wettest year 1931			1.67	5.83	2.54	8.29	7.46	9.45	9.56	5.54	10.61	6.40	15.64	4.57	87.55
Driest year 1946			2.97	1.67	1.46	1.64	7.08	5.20	3.97	4.78	3.86	3.45	3.50	3.05	42.56
Ponce (40 ft above sea level)															
Minimum	1899	1953	0.03	T	0.00	0.03	0.18	T	0.02	0.32	0.67	0.81	0.21	T	....
Mean	1899	1953	1.05	1.10	1.11	2.08	3.94	3.33	2.61	4.39	5.18	5.82	4.19	1.22	36.02
Maximum	1899	1953	5.13	8.72	5.09	5.50	13.04	16.68	8.26	17.20	12.64	16.46	11.05	4.27	....
Wettest year 1909			1.34	0.86	0.45	2.62	3.69	7.74	3.14	17.20	3.19	8.20	10.20	0.10	58.73
Driest year 1929			0.05	0.56	0.54	1.67	2.03	0.89	0.20	2.52	7.75	1.74	0.87	0.97	19.79

to time and may cause considerable loss of the sugar cane and other crops. The drought which struck the Fajardo valley at the extreme eastern end of the north coast in the late winter of 1952 and spring of 1953 almost caused the total loss of the crop of the Fajardo Sugar Central. In the fall of 1953 silver iodide cloud seeding with ground generators was underway in an attempt to increase the rainfall on the plantation.

Irrigation is required for sugar cane in the less humid section in the western part of the north coast where about 50 inches of rain falls in a normal year, and exceedingly porous limestone soils accentuate the dryness.

On the south coast sugar cane does not provide economic yields in areas having less than 60 inches of rainfall unless irrigation is practiced. Many of the farmers of the south coast who have been urging the Water Resources Authority to undertake rainmaking experiments think of rainmaking in terms of alleviating the droughts that are common there. They do not realize that due to the lack of suitable clouds during drought periods on the south coast, cloud seeding is not feasable. The south coast will continue to be a region of drought and deficient rainfall (30 to 50 inches). However, by seeding in the mountains to the north during the drought period on the coast, it may be possible to furnish sufficient water for the mountain reservoirs so that additional irrigation water may be available to mitigate the effects of the drought.

Although some rain falls throughout the year in the mountains, additional rainfall is desired during the drier months, December through April, for the reservoirs. The water is used in the generation of water power and then for irrigation on the south coast. Because of the greater water supply available in the streams draining the north slope, the Authority has dammed many of the northward flowing streams and diverted the surplus water to the south coast by tunneling through the mountains [PUERTO RICO, 1948].

The Public Irrigation Law fixed the amount of 48 inches per year of irrigation water as appurtenant to the 51,000 acres of land comprised in the South Coast Irrigation District. [LUCCHETTI, 1945]. In the Isabela Irrigation Service on the western part of the north coast, the allotment is 18 inches per year. This is the quantity that was estimated as necessary to supply the deficiency in rainfall in most years.

The quantity of 48 inches per year has proved sufficient for a good part of the land included in the South Coast Irrigation District; but for the porous sandy soils, it falls short of meeting the irrigation requirement [KOENIG, 1953]. To supply this deficiency, the planters have tapped the underground water. Observations made at Central Aguirre on the south coast show that sugar cane there can utilize from 100 to 160 inches of water a year (including water lost by deep percolation during irrigation). This is supplied by 45 inches of rainfall, 48 inches of irrigation water purchased from the South Coast Irrigation Service, and by 50 inches of underground water pumped from the subsoil. Because of the drain on the underground water supply, the water supply and height of the water table has been decreasing during the past several years. Thus, additional rainfall on the south slopes of the mountains and the south coast to replenish the water table would be welcome.

Cloud seeding studies of Puerto Rico and neighboring islands--In evaluating the possibilities for rainfall stimulation through cloud seeding with silver iodide ground generators, a search was made of the literature on Puerto Rico and the neighboring islands. SCHAEFER [1949, 1953] has reported observations of seeding conditions in Puerto Rico and vicinity and some experiments with water seeding. References to this material are included in subsequent parts of the analysis. Two studies were found concerning seeding conditions in Cuba which has a somewhat similar climate to that of Puerto Rico [HOWELL, 1953; AMERICAN INSTITUTE OF AEROLOGICAL RESEARCH, 1952]. These studies were concerned with the influence of large scale synoptic patterns -- easterly waves, throughs, polar fronts, etc. -- on the rainfall of Cuba in relation to the possibilities for silver iodide cloud seeding in Cuba. However, the suitability of the clouds and atmospheric conditions (such as the height of the -5°C level, the effective level for silver iodide) were not considered in either study.

The effective level of silver iodide seeding--Numerous researchers have established the fact that spontaneous crystalization of water droplets in supercooled water clouds occurs at -40°C and that silver iodide first becomes effective as a nucleating agent in supercooled clouds at about -5°C. The -40°C level is found at 35,000 ft in Puerto Rico. V. J. Schaefer informed the writer that in February, 1949, he flew through a huge cumulonimbus cloud mass over Puerto Rico that towered above 40,000 ft. It was composed of ice crystals that had without doubt been formed by spontaneous freezing of water droplets at this high level in the atmosphere. The cloud dissipated without yielding any rain.

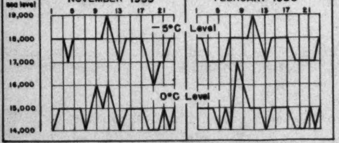

Fig. 3--Height of the 0°C and -5°C levels at San Juan, Puerto Rico

Figure 3 shows the height of the 0°C and -5°C levels at San Juan, Puerto Rico, in November and February, 1953 (based on the 15h 00m GST radiosonde). Noteworthy is the fact that there is scarcely any variation in height with season, the 0°C level being between 14,000 and 15,000 ft and the -5°C level between 17,000 and 18,000 ft throughout the year.

These levels are typical of the tropics. For example, DAVIES [1952] reported that in Tanganyika, Africa, the height of the -5°C level automatically restricts the silver iodide seeding experiments to occasions when the cumulus clouds reached above 18,000 ft.

At San Juan a cloud would have to build to above 17,500 ft to be influenced by silver iodide, assuming that the silver iodide reached that level in the cloud. Most clouds that build that high in Puerto Rico are already producing rain before they reach that height or will yield rain naturally without the presence of silver iodide.

Warm-cloud rainfall in Puerto Rico--Most rain in Puerto Rico is believed to fall from clouds that do not reach the level where silver iodide will be effective. Observations by the writer and conversations with other meteorologists and pilots on the Island indicate that much of the rain of the Island and vicinity falls from cumulus clouds that complete their life cycle below 0°C level [ALPERT, in press]. All rain showers observed by the writer during November, 1953, fell from clouds whose tops were estimated (at the time rain was first seen) at only between 8000 and 12,000 ft above sea level. Other meteorologists on the Island and pilots confirm the fact that these levels are typical not only of November but of all seasons.

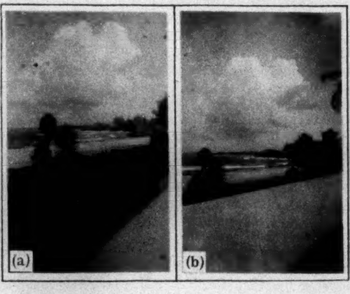

Fig. 4--Warm cumulus rain cloud at San Juan, Puerto Rico, November 10, 1953: (a) view east at 13h 30m LST; (b) view east at 13h 34m LST

Figure 4 shows a warm cumulus rain cloud at San Juan on November 10, 1953. The top of the cloud is estimated to be between 11,000 and 12,000 ft above sea level. According to the San Juan morning and afternoon radiosonde, the 0°C level was at 15,000 ft and the -5°C level at 17,500 ft. Note the absence of middle or high clouds and the hard outline of the cloud. The whispy section in the saddle at the top of Figure 4b represents all that is left of an evaporating tower. This is a typical situation and many other showers were observed to fall from similar clouds.

Recently MORDY and EBER [1954] reported similar conditions for the Island of Oahu, Hawaii. On each of ten days of observation, rain fell from warm clouds with tops between 6000 and 8000 ft where the temperature in all cases was warmer than 7°C, the freezing level being about 14,000 ft. Their additional observations that rainfall from warm clouds is very frequent and contributes substantially to the total rainfall for some areas, and that large amounts of rainfall can occur from warm clouds with only moderate vertical development also appear to be applicable to conditions observed in Puerto Rico.

Since most clouds that were observed to yield rainfall complete their entire life cycle below the 0°C level, they are not subject to supercooling. In winter in particular, it would appear that the trade inversion is usually sufficiently well developed (such as during the period of observations in February, 1949, shown in Fig. 5) so that cloud tops are confined below the 8000-to-12,000-ft level, well below the level of supercooling.

Only a small proportion of the clouds yielding showers were observed to grow above the 0°C level after the showers were well underway at levels well below the 0°C level. In fact no clouds were observed by the writer to grow above the 0°C level and give rain that had not already been raining when the tops were between 8000 and 12,000 ft. This would suggest that there are always sufficient nuclei in the air (possibly salt nuclei) to initiate the rainfall cycle at the low levels. However, it is likely that some clouds build above the 0°C level before giving rain and freezing nuclei come into play.

Although information is lacking as to the proportion of the total rainfall that falls from the warm rain clouds that build vertically above the 0°C level, it is believed that these clouds yield the heaviest showers.

Danger of increasing rainfall--The assumption that heavy showers are more likely to fall from the clouds that grow above the 0°C level is significant from another point of view. In several experiments in cloud seeding with a variety of chemicals and techniques (for example, LEOPOLD and HALSTEAD [1948]), it has been reported that shortly after seeding a rain shower, the intensity of the

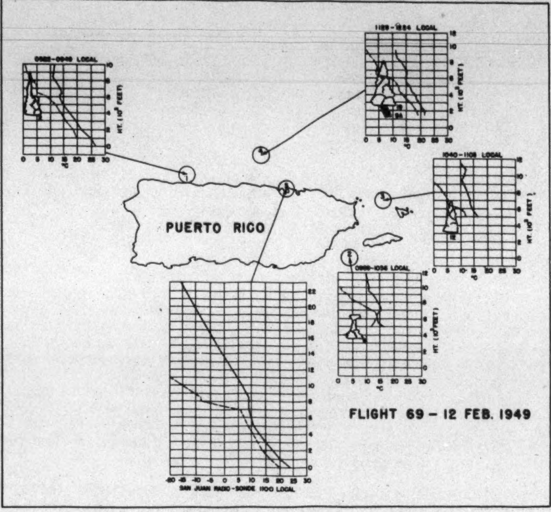

Fig. 5--Temperature-moisture sounding in the vicinity of Puerto Rico, 09h 22m to 12h 24m LST, February 12, 1949 [after SCHAEFER, 1953]

rainfall increased markedly. Some commercial cloud seeders point to this phenomenon and claim that they do not make rain but rather stimulate clouds to yield more rain than they would have yielded naturally.

In Puerto Rico very intense showers are not uncommon from the clouds that grow above 17,500 ft where silver iodide is effective. The table of maximum 24-hr rainfall recorded in Puerto Rico during the different months in the 50-year period 1899-1950 published by QUIÑONES [1945] indicates that quite heavy falls of rain may occur in any month (see Table 2). The seeding of a cloud from which rain is already falling may result in extremely intense falls of rain in a very short period of time causing destructive flash floods and damaging erosion particularly on the mountain slopes. Some reservoirs are silting up at an alarming rate and some have lost half their storage capacity due to silting [LUCCHETTI, 1945]. On November 17, 1953, the writer was present in San Juan during a thunderstorm that yielded 1.30 inches of rainfall at the city office and 2.67 inches at the airport office about one mile away in only a few hours. The lower lying sections of San Juan were flooded.

These heavy falls of rain, more than one inch in 24 hr, are also undesirable from the point of view that they contribute little more to the crops than a lighter rain which does not have the destructive characteristics [FUHRIMAN and SMITH, 1951]. Observations at Central Aquirre on the south coast have shown that generally, if a rainfall of less than one inch in one day occurs in the south coastal plain area, there is no runoff, that is all of the water is absorbed by the soil, which is desirable. However, with a daily rainfall in excess of one inch a high percentage was lost by surface runoff or by subsoil seepage unless the soil was very dry.

Thus, it would be dangerous or undesirable in many cases to seed the few situations that are susceptible to silver iodide seeding.

Table 2--Maximum 24-hr rainfall recorded in Puerto Rico (1899-1950)

Date	Place	Amount
		inch
January 23, 1901	Coamo	8.10
February 5, 1938	Quebradillas	7.10
March 3, 1933	Mayaguez	17.40
April 23, 1900	Luquillo	12.33
May 6, 1928	La Fe	12.20
June 11-12, 1919	Canovanas	14.83
July 6, 1901	Luquillo	17.02
August 8, 1899	Adjuntas	23.00
September 7, 1910	Naguabo	18.22
October 15, 1943	Carite Camp	14.10
November 13, 1919	Yabucoa	12.90
December 13-14, 1910	San Juan	10.55

Schaefer's observations of warm-cloud rainfall in Puerto Rico--The writer's observations of warm-cloud rainfall in November toward the end of the rainy season are supplemented by those made by SCHAEFER [1949, 1950, 1953] in February, 1949, at the height of the dry season. Schaefer and other members of the Research Group of the General Electric Research Laboratory working on Project Cirrus were surprised to see heavy rain falling from these warm cumulus clouds for it was believed at that time by some meteorologists that such clouds do not yield rain. The temperature-moisture sounding in Figure 5 published by SCHAEFER [1953] indicates that a rain shower off the north coast is falling from a warm cumulus cloud whose top is at 8000 ft above sea level where the temperature is 12°C. According to the sounding at San Juan, the 0°C level is at about 13,500 ft, some 5500 ft above the top of the rain cloud. The -5°C level is at about 16,500 ft, some 8500 ft above the top of the rain cloud.

SCHAEFER [1949] reported further that very thin stratus clouds were seen to produce virga and sometimes yield fairly substantial light rain for extended time periods. On some days it was observed that practically every cloud approaching the size that would be suitable for water-seeding experiments showed natural rain development. One of the outstanding features noted in such clouds was the fact that despite relatively low vertical velocities and lack of hard surface cumulus or extensive vertical development, rain occurred very frequently. On other days it was observed that the clouds had much less of a tendency to produce rain. Many times clouds that appeared similar to those producing rain naturally were seen to form and dissipate without yielding a trace of precipitation.

Effect of trade inversion--Figure 5 illustrates another significant fact about the use of silver iodide ground generators in Puerto Rico during the dry season, December through March or April, when rainfall is needed most. During the dry season a temperature inversion (the trade inversion) is present between 3000 and 12,000 ft above sea level, which is largely responsible for the dry weather. Vertical currents are suppressed and any silver iodide particles released at the ground would not ordinarily penetrate to high levels as they would be trapped in the layer below the inversion. Examples of the efficiency of an inversion in confining air borne material released below it are given by the Los Angeles smog and the Donora pollution disaster. In both cases well-developed inversions trapped the pollutants which in the absence of wind motion may accumulate to annoying and even dangerous concentrations. We have a report from Australia by Bowen (related to the writer by H. Wexler) that a temperature inversion during a cloud-seeding experiment trapped silver iodide smoke and confined it to a layer only 1600 ft deep.

An additional deterrent to the use of silver iodide during the dry season is the fact that well-developed cumulus clouds are scarce except for occasional developments over the rainy windward mountain slopes. SCHAEFER [1949] reported that in February, 1949, the strong inversion between 8000 and 12,000 ft and dry air aloft prevented the development of supercooled clouds and rain occurred only from relatively small cumulus clouds generally after they encountered the inversion and flattened out to form a sort of stratus. Rain clouds often resembled anvil tops, although no part of the cloud ever reached the freezing level.

Effect of sunlight--Another factor to consider in evaluating the practicability of silver iodide seeding is the possibility that silver iodide loses much of its effectiveness for causing ice crystals to form in supercooled water clouds soon after leaving the ground generator because the decay rate of silver iodide freezing nuclei is critically dependent on the ambient air temperature [BOLTON, 1954]. A decrease of freezing nuclei concentration to one-tenth of the initial value takes place in two to eight minutes at 65°F and in less than one minute at 90°F. Since at sea level over the Island the mean daily maximum temperature ranges from 80° to 90°F and the mean daily minimum temperature from 65° to 75°F during the year, smoke released from the ground generator in the warm air is of little use.

Silver iodide smoke released at night from ground generators to escape destruction by the high afternoon temperature will ordinarily be trapped under the surface air inversion formed by nocturnal cooling of the ground and thus not reach the upper levels before daybreak and high temperatures. In addition, most particles released at night would be carried out to sea or would be so widely dispersed over the Island that it would be impossible to confine the seeding influence to the particular areas where additional rainfall is desired.

Confinement of rainfall to particular areas--Confinement of rainfall to particular areas is important because of the requirement of the Water Resources Authority that rainfall produced by the cloud seeders be confined to particular areas in the mountains and does not fall where rain is not wanted. The Authority wants additional rainfall in the mountains during the period December through April (and in some drought years through July) at a time when the coffee and tobacco growers in the mountains and the sugar growers on the coast may not want rain.

In addition, although unseasonal heavy rains in any month are by no means infrequent due to natural causes as indicated in Tables 1 and 2, they would without doubt be blamed on the rainmakers as long as it is known that a program of cloud seeding is underway anywhere on the Island.

Confining rainfall to precise localities in the mountains or on coastal lowlands using silver iodide ground generators is not believed to be feasible in Puerto Rico. The silver iodide generators release an enormous number of minute particles into the air which partake of the complex motion of the surface air, diffusing as they move so that they become less and less concentrated. The particles are carried by the wind aloft far beyond the place of release. Techniques for predicting the movement of the particles are crude and in a difficult forecast situation such as is presented in Puerto Rico, one questions whether any high degree of accuracy could be attained in predicting the movement of the particles.

In addition, depending upon the particular winds and vertical temperature distribution which are very complex due to the mountains and the trade inversion, the particles may or may not ascend to the upper regions above 17,500 ft where suitable supercooled water clouds might exist.

Conclusions--We must recognize that large gaps exist in our knowledge of clouds, rainfall, and related atmospheric conditions in Puerto Rico as well as the mechanism by which silver iodide acts to cause nucleation of supercooled clouds. Nevertheless, it appears that insufficient attention has been paid to the meteorological factors that would influence cloud-seeding experiments by those advocating the use of silver iodide for stimulation of rainfall in Puerto Rico and other places in the Caribbean. The combination of atmospheric conditions noted by field observations and evidence in the weather records for the area, and the rigid space and time requirements for rainfall specified by economic considerations do not suggest much success can be expected from cloud seeding with silver iodide ground generators. Silver iodide may be effective in a relatively small number of cases mainly in the rainy season when the need for additional rainfall is not as acute as in the dry season. These few cases when silver iodide will be effective may be dangerous to exploit due to our inability to confine the rainfall to specific areas where it is wanted and the possibility of causing excessive falls which result in floods and erosion. During the droughts on the south coast, cloud seeding is not possible because of the absence of suitable clouds.

The greatest hope for rainfall increase appears to be centered in the stimulation of rainfall from clouds that do not reach up to the freezing level and would not respond to silver iodide seeding. These are the warm clouds that occur in such numbers almost every day and probably yield much of the rainfall of the Island. For these warm clouds other chemicals such as dry ice, water droplets, and sea-salt crystals are believed to be most effective. James P. Lodge of the Cloud Physics Project, University of Chicago, informed the writer in 1954 that on the basis of observations in 1953 and 1954 in Puerto Rico there always may be sufficient sea salt crystals in the air over Puerto Rico so that the addition of sea salt crystals may not offer much possibilities for stimulating rainfall. SCHAEFER [1949] and D. C. McDowell (University of Puerto Rico) tried water seeding without any success, possibly because bulk water was dropped into the top of the cloud rather than introduced as droplets into the base of the cloud as has been the practice in Australia.

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A COMPARISON OF STEP-, PRESSURE-, AND CONTINUOUS-WIRE-GAGE WAVE RECORDINGS IN THE GOLDEN GATE CHANNEL

J. R. Gerhardt, K. H. Jehn, and I. Katz

Abstract--Step-, pressure-, and continuous-wire-type wave gages were installed on a steel pile located in 35 to 40 ft of water approximately 600 ft off the northeastern end of Baker's Beach, San Francisco. Simultaneous measurements with all gages were made on a nearly continuous basis during most of April, 1953. These data have been evaluated to obtain characteristic wave periods and heights, height probability distributions, autocorrelation functions, and power spectra. In addition, direct recordings of wave slopes were made possible by using a three-wire continuous-wire gage, and a brief description is given of certain of the characteristics of these data. While the frequency responses of all three instruments were nearly identical, surface waves derived from the subsurface pressure-gage recordings were shown to underestimate true values by an average factor of about 25 pct. The rather complex oceanographic structure of the channel is emphasized by occasional well-marked surges having periods of about three minutes with heights up to one foot and by significant changes occurring in the characteristic wave period.

Introduction--During the period from late January through April, 1953, personnel of the Electrical Engineering Research Laboratory conducted certain microwave radio propagation tests off the California coast near San Francisco, with the test area located seaward from the Golden Gate Bridge. In connection with these tests, meteorological and oceanographic measurements were taken to describe the structure of the atmosphere and the water surface along the radio path. Figure 1 shows the general area of the research project. The principal objectives of this paper are to describe the associated water-surface measurement program and to present certain comparisons between several types of wave-sensing elements.

Instrumentation--A stable platform from which to measure the water waves in this channel in relatively deep water was obtained by driving an 18-inch diameter steel pile in 35 to 40 ft of water, 200 yd off the northern end of Baker's Beach.

Three different types of wave gages were mounted 2.5 to 3.5 ft to seaward of the pile. These were (1) a parallel-type step gage having 71 electrodes spaced at 0.2 ft intervals, (2) a 15-ft long three-wire continuous-wire gage, and (3) a Mark IX pressure gage. The step gage was constructed at this Laboratory following the design described by CALDWELL [1948] and shown schematically in Figure 2. Automobile-type spark plugs were inserted into the mast along its 14-ft working range, with the interior of the mast being sealed off from the sea by entrapped air maintained at a pressure of about 60 psi. Neoprene paint and silicone grease water-repellent coatings were added to the insulators and the mast down to the level of the bottom electrode to minimize leakage currents and resulting calibration non-linearities due to water film remaining on the gage. That the problem was essentially resolved is evidenced by the fact that a clear step function in the recording can be seen when the water rises past an electrode; leakage currents would have smoothed the steps. In the case of a falling water level, the finite time for water runoff even with a water-repellent coating will invariably act in a step-type gage to smooth the step function. A calibrator was constructed by simulating the step gage, its resistors, and the sea cable by an electrical network with adjustable elements to duplicate the effect of various water levels, although when the individual steps can be detected in the recording the step gage is a continuously self-calibrating device.

The continuous-wire gage (Fig. 3) was installed beside the step gage. This gage made use of the general features of a continuous-wire gage developed by Duntley which was successfully used to make height and slope measurements in fresh water. (No published account of Duntley's work is available.) Very briefly, this system measures the height of the water surface by measuring the change in resistance from the top end of a long vertically held wire immersed in water to another electrode held under water. If two wires are used, it is possible to measure the difference in height and thus approximately the slope of the water surface in the plane defined by the two wires. A complete description of this device can be found in a report by JEHN and Others [1954]. Wave slopes were measured in two directions at right angles to each other, one essentially parallel and the other

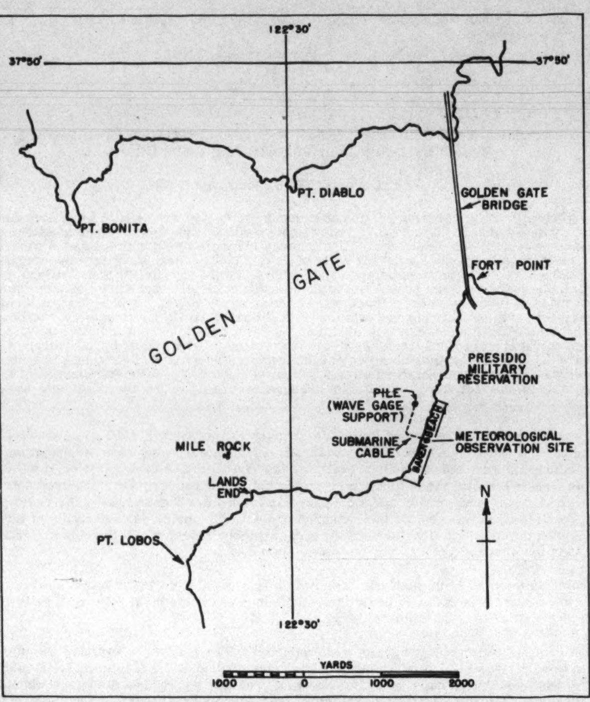
122°30'
37°50'
37°50'
PT. BONITA
PT. DIABLO
GOLDEN GATE BRIDGE
FORT POINT
GOLDEN GATE
PRESIDIO MILITARY RESERVATION
PILE (WAVE GAGE SUPPORT)
BAKER BEACH
METEOROLOGICAL OBSERVATION SITE
SUBMARINE CABLE
MILE ROCK
LANDS END
PT. LOBOS
N
122°30'
YARDS
1000
0
1000
2000

Fig. 1--Site of oceanographic and meteorological measurements in Golden Gate Channel

perpendicular to the average direction from which the swell approached the pile. While the continuous-wire gage is superior to the step gage in that it has a greater potential accuracy in measuring small waves than the step gage whose sensitivity is limited by the discrete electrode spacing, its lack of an accurate calibration device is a drawback. An electronic simulator was used as a calibrating mechanism for the slope device, while the step gage was used as the calibration for the single-wire amplitude measurements. It would appear that a combination of a continuous-wire gage with relatively wide-spaced step-gage electrodes would prove to be the most effective means of accurately measuring water surface variations.

The Mark IX pressure gage [SNODGRASS, 1952] was made available on loan from the University of California at Berkeley. It was attached to the lower end of the step-gage mast as shown in Figure 4.

The outputs of all three gages were recorded simultaneously on a rapid-speed four-channel Edin recorder. An Esterline-Angus meter was also used for individual recording of the pressure-gage signal. Simultaneous observations with all gages were normally made during 15-min periods ten to 20 times throughout the day at a recording speed of 2.5 to 5.0 mm/sec.

General oceanography of the Golden Gate--Although the Golden Gate radio path had many of the desired geometrical characteristics for a careful study of the reflection of microwave radio energy from water surfaces of varying degrees of roughness, the channel itself has a rather

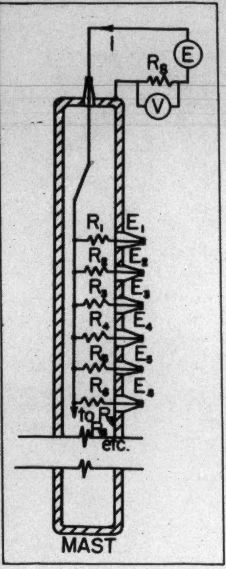

Fig. 2--Schematic diagram of step gage

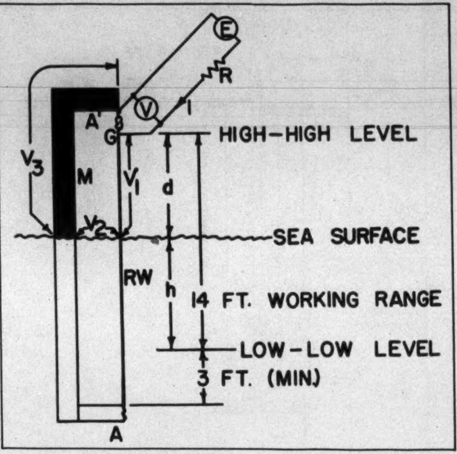

Fig. 3--Schematic diagram of continuous-wire gage

complex associated oceanography. Currents in the channel were quite strong, and standing wave patterns formed by the interaction of the outflow and inflow currents appeared as the rule rather than as the exception. Significant horizontal variations in the wave structure could often be observed visually over the entire outer portion of the channel. The deep basin nature of the channel also appeared on occasion to be responsible for the appearance of surge-type water surface variations similar to those reported on coastal installations by MUNK [1949] and YOSHIDA [1950] and which would not be representative of open water conditions. Thus on April 22, for instance, waves having periods of 2.5 to three minutes and heights up to one foot were noted in both the pressure- and step-gage recordings. Although a thorough examination of the data has not been made, significant surge effects were noticeable only on April 22 with some indications present on April 23 and 24. However, whether this represents some natural vibration frequency of the channel or, as suggested by Yoshida, a frequency present (but of possibly too low an amplitude to be detectable) in all wave patterns near shore locations cannot be determined. An example of this wave pattern is shown in Figure 5.

The analysis of the wave-gage data has proceeded along two major lines. The first, which may be termed a statistical approach, is still underway and will be reported separately. In this analysis, extensive use is being made of a correlation computer, and the results are largely in terms of autocorrelations, probability distributions, and power spectra. The second approach has been what might be termed a synoptic one, with emphasis on the broad scale features of the wave patterns. This analysis has been semi-statistical, and has used limited portions of the data to characterize such variables as wave period, wave heights, and wave-height ratios for the entire period of observations. In addition, a comparison of the records obtained from the three wave gages has been made and the results are reported.

The output of the University of California pressure gage was recorded nearly continuously on a motor-driven Esterline-Angus 0-1 milliampere recorder at a paper speed of 1.5 inch/min. The data have been analyzed according to the method outlined by SNODGRASS and STILING [1951] and based on the concept that an observer's estimate of average wave height is equivalent to the average of the significant or highest one-third of the waves that pass a given point. This method will hereinafter be referred to as the significant wave method. Representative 20-min periods were selected for mornings and afternoons by visual inspection of the original records for the period April 6 to 27, 1953. From these sets of data were found: (a) characteristic wave period T in seconds (defined

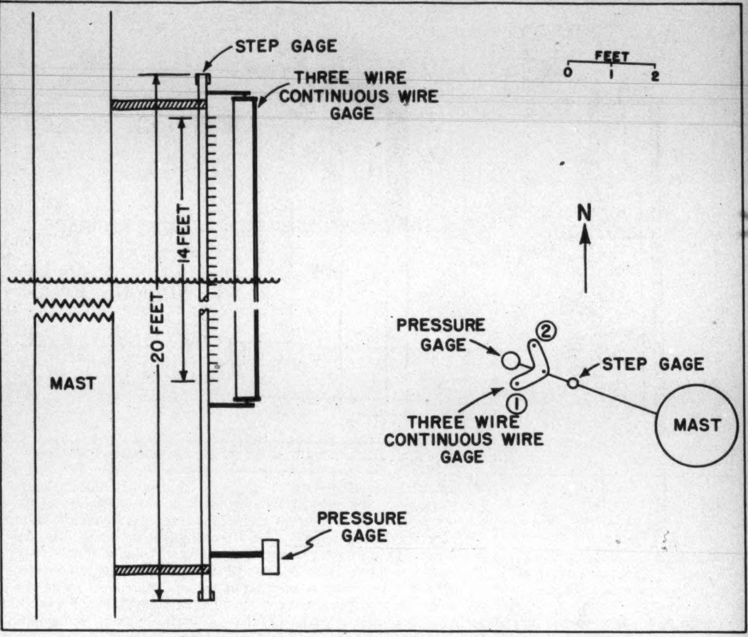

Fig. 4--Relative positions and orientations of the three wave gages

as the average period for the well-defined series of highest waves observed during the 20-min period); (b) characteristic wave height $H_{1/3}$ in feet (defined as the average height in the highest third of the well-defined waves); (c) maximum wave height H_{max} in feet (highest wave recorded in the 20-min interval); and (d) the ratio of H_{max} to $H_{1/3}$. The results of this analysis appear in Figure 6.

In addition, in part to check the apparent representativeness of these points and to check the time trends of these variables, a second set of 20-min periods of data was chosen from the Esterline-Angus trace. Here, an effort was made to select data for a time for which no analysis had been made rather than for the most representative data during a morning or an afternoon. These points are plotted on Figure 6. There are no systematic differences between these two sets, suggesting that the time trends of wave periods and wave heights are not distorted materially by the choice of analysis periods.

It is seen that the characteristic wave period decreases uniformly from ten seconds to about seven seconds over the period April 6 to 13, then increases sharply to near 15 sec less than 24 hr later. Groups of significantly high waves are difficult to discern prior to April 14, and the overall pattern is one of numerous relatively low waves, with a reasonably uniform wave length or wave speed (or both). On the morning of April 14, however, groups of significant waves again appeared; these waves were longer or slower (or both) than those of April 13, with the result that the computed characteristic wave period more than doubled, although wave heights showed no material change. To what extent this increase in period is peculiar to the inlet itself and whether it is representative of conditions over the entire Golden Gate area, however, cannot be determined from the data at hand. True, the Lightship ten miles to seaward, in 108 ft, reported no such change, and

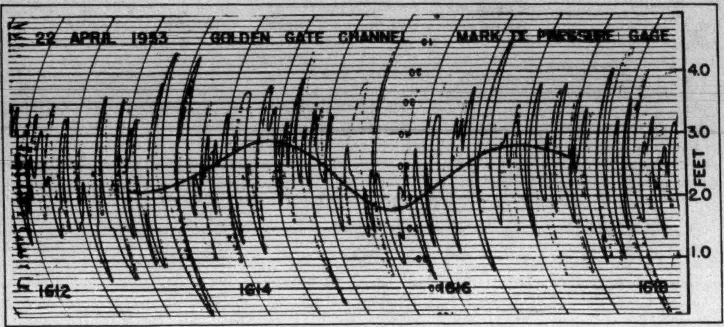

Fig. 5--Section of original recording of pressure-gage data showing surge-type waves; the solid curve from 1613 to 1617.5 is a visual estimate of average water-level variation

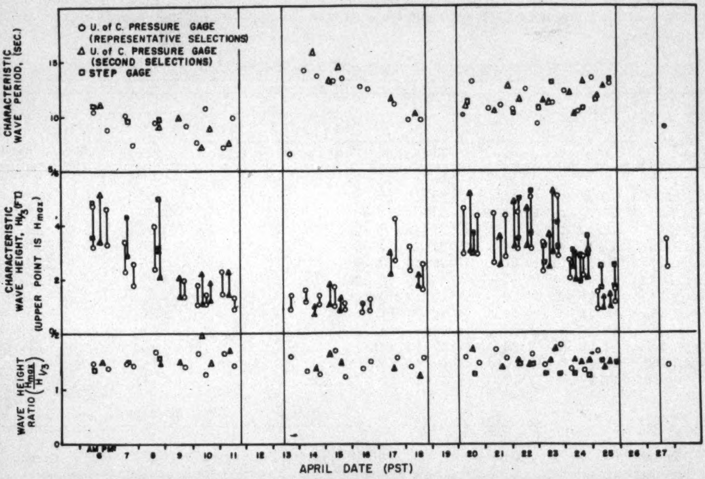

Fig. 6--Summary of pressure-gage and step-gage evaluations of characteristic wave period, wave heights, and $H_{max}/H_{1/3}$ ratios for April 6 to 27, 1953, observation program; all computations made from approximate 20-min samples by significant wave method

periods of waves passing the Lightship were always in the order of five or six seconds, with no significant change reported during the entire period April 6 to 27. However, the lower and constant wave period from the Lightship may well be as much a result of the consequence of counting all waves rather than only groups of significant waves, as it is a consequence of the open water location of the Lightship.

Finally, the H_{max} to $H_{1/3}$ wave-height ratios in Figure 6 are seen to average near 1.5 for the entire period of record, with overall variations from 1.2 to 2.0. This finding is at some variance with identical ratios reported in the literature from different sources. WIEGEL [1949], for instance, reports an average value of daily ratios of 1.87 for three exposed locations on the Pacific Coast taken for time intervals from three to 12 months, a value considerably in excess of 1.5. However, a part of this difference can undoubtedly be explained by the fact that Wiegel's procedure for obtaining daily values of the ratio involved using for H_{max} the maximum wave height occurring over any of three successive 20-min recordings taken at eight-hour intervals and for $H_{1/3}$ the average of the three corresponding 20-min $H_{1/3}$'s. Nevertheless, the suggestion is strong here that the records from the Golden Gate location cannot be compared with those obtained from more exposed coastal locations like Point Arguello and Cuttyhunk. The relatively short record of one month obtained during the test period must also be kept in mind.

Comparison of various gage recordings--The same significant wave method of analysis was applied to a limited number of the step-gage recordings, and the results again plotted on Figure 6. It will be noted that in general the step-gage findings agree with those of the pressure gage, with an important exception in the characteristic ($H_{1/3}$) wave heights. It will be noticed from Table 1, which gives the comparable $H_{1/3}$ values for step- and pressure-gage recordings, that with one exception the actual wave heights measured with the step gage exceed those computed from the pressure-gage record. Although the times are not always synchronous and there are only a few data available for comparison, the average pressure-gage wave heights are certainly about 25 pct too low. Whether or not the extremely high ratio indicated for April 25 is real has not been determined, but there may be an indication in these data that the height discrepancy might be an inverse function of wave amplitude. Comparison between step- and pressure-gage records will be explored further in a later section.

Table 1--Comparison of significant wave method of $H_{1/3}$ evaluation for pressure- and step-gage data

Date	Time		$H_{1/3}$		$H_{1/3}$ ratio step/pressure
	Pressure gage	Step gage	Pressure gage	Step gage	
	h m h m	h m h m	ft	ft	
April 6	10 40 to 11 00	10 41 to 11 01	3.2	3.55	1.11
April 7	13 31 to 13 48	13 31 to 13 48	2.3	2.89	1.26
April 8	16 10 to 16 30	16 00 to 16 20	2.1	3.17	1.51
April 20	12 50 to 13 10	13 51 to 14 08	3.0	2.90	0.97
April 22	10 00 to 10 20	10 03 to 10 18	3.1	3.45	1.11
April 22	15 44 to 16 04	15 43 to 15 58	3.2	3.60	1.12
April 23	09 30 to 09 50	10 16 to 10 32	2.3	2.55	1.11
April 23	16 19 to 16 39	15 54 to 16 10	2.8	3.20	1.14
April 24	11 10 to 11 30	10 42 to 10 58	2.0	2.41	1.20
April 24	17 08 to 17 28	17 05 to 17 25	2.0	2.90	1.45
April 25	11 40 to 12 00	11 00 to 11 15	0.94	1.65	1.76
April 25	17 27 to 17 47	17 27 to 17 47	1.1	1.71	1.55
				Average	1.27

In a further effort to assess the nature of the departure of pressure-gage computed waves from actual wave heights, the pressure-gage and step-gage records were further compared in detail. The initial comparison has been mentioned and is shown in Figure 6. However, to explore the discrepancy more fully, 20-min intervals were chosen when both step-gage and pressure-gage records were available so that exactly the same groups of waves were available for comparison. Moreover, the records were carefully examined to the extent that identical waves were being compared, within the limits of human error in comparing Esterline-Angus records with the Edin records. Owing to the greater detail in the step-gage water-surface recordings, it was not possible to determine identical waves in both recordings where the heights were less than about one foot. The results of the comparisons of these identical waves for two 20-min periods of April 24 and 25 are shown in Figure 7. Here are plotted actual wave heights (from the step gage) against wave heights computed from the pressure-gage record, using a different mean K for each of the two sets of pressure-gage data. It is apparent that the wave heights computed from the pressure-gage record are smaller than the actual waves by a large factor. The slopes of the two dashed lines are

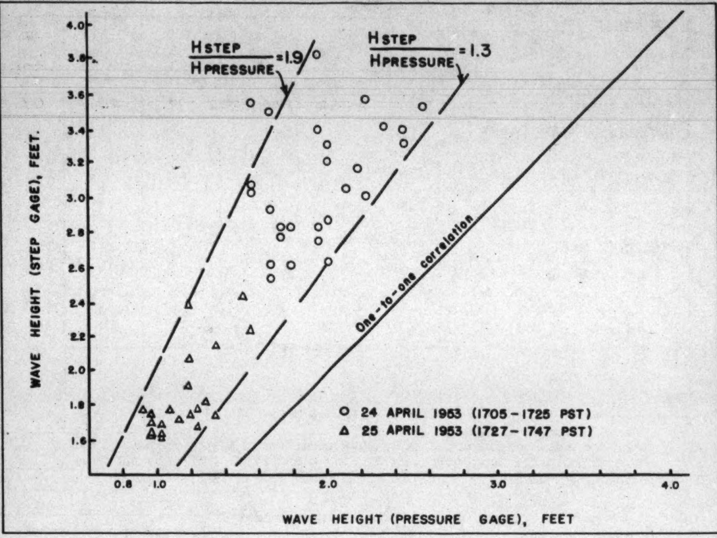

Fig. 7--Wave for wave-height comparison of step- and pressure-gages for two 20-min periods

1.9 and 1.3, respectively; a best-fitting mean curve would give a ratio of step-gage height to pressure-gage height of about 1.45. Moreover, the uncertainty of the computed wave height becomes larger for larger waves, as shown by the greater scatter of the points at the upper end of the plot. It is admitted that these data are limited in amount; however, it has been possible to compare wave heights, virtually wave for wave. That these findings are not new to the oceanographer is illustrated in a paper by FOLSOM [1949] where average factors ranging from 1.07 to values as high as 1.35 have been determined as necessary to correct observed pressure-gage readings to obtain true water-surface variations. Although it has not been possible to carry this phase of the analysis any farther, a fairly complete selection of simultaneous step- and pressure-gage data is available for further study. Since one of the major drawbacks to the significant wave method of evaluating $H_{1/3}$ lies in the assignment of a single correction factor K to an average period which actually consists of a continuous spectrum of wave periods, it would appear that a very real refinement of the method would result if it were possible to apply a continuously variable K to the complete spectrum of wave periods.

The continuous-wire gage had its output placed on a second channel of the Edin recorder, making a simultaneous record with the step gage. There was an obvious one-to-one correlation of the two records such that the need for a detailed analysis of the continuous-wire records was obviated. The essentially identical patterns of the step and continuous-wire gages and the marked loss of sensitivity for the pressure gage can be seen very easily in Figure 8, which shows a representative and simultaneous set of recordings of the outputs of all three gages. It can be noted that waves having periods of one to two seconds are completely missing from the pressure-gage record and waves with periods up to three to four seconds have a considerably reduced height. Note in the step-gage output that clearly defined steps can be seen only during periods when the water surface is rising.

Further details of the comparison between step and continuous-wire recordings with particular emphasis on the record obtained from the wave slope units of the continuous-wire gage are shown in Figures 9 through 12. Visual inspection of these simultaneous height and slope wave records shows some very interesting features, and although no significant analysis of the slope data has

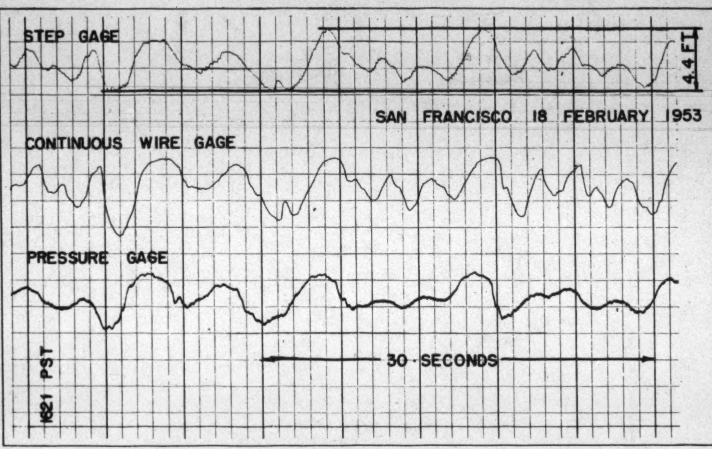

Fig. 8--Section of original simultaneous recording of step-, pressure-, and continuous-wire (amplitude) gage data for February 18, 1953; apparent phase lead of pressure-gage results from a recording pen of different length

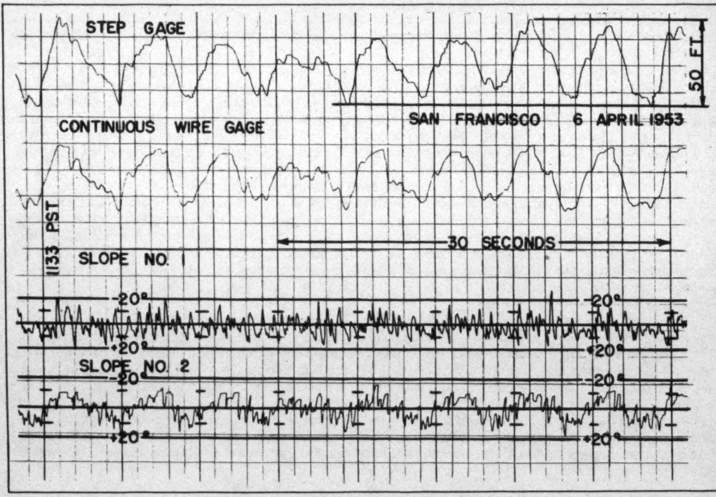

Fig. 9--Section of original simultaneous recording of step- and continuous-wire (height and slope) gage data for April 6, 1953 been made, one can, in a sense, reconstruct the characteristics of the water surface at the pile by the comparison of the two records. The data for April 6, for instance, shown in Figure 9, contain some of the highest waves noted during the entire observation period, and there is a marked difference between the two slope recordings in contrast to their more normal essentially similar patterns. The obvious correspondence of the same fundamental swell period in both the height and Slope 2 records would indicate that the high waves are sufficiently steep so that a slope-measuring device operating over a distance of six inches is sufficient to describe both the major wave profile and the superimposed smaller water-surface variations. The lack of this major period in the Slope 1 record would appear to indicate that the wave crests are traveling essentially parallel to the Slope 2 direction, that is, from the northwest.

Two other features of the slope records might be worth pointing out. The frequencies in the slope variations are, as is to be expected, much higher than those for the amplitude variations. These changes, however, can on occasion be so rapid as to give essentially vertical lines on the recordings. Since the height traces never show such high-frequency effects, they must be due to some combination of rapidly moving, forming, or dissipating water-surface perturbations of very short wave length (of the order of six inches) superimposed on the ordinary sea structure. A few such instances can be noted in the slope recordings shown in Figure 9. Finally, we can see in the Slope 2 recording of the same figure some very unusual flattened traces. Since there is no reason to suspect instrument malfunctioning, sections of the profiles of relatively large waves appear to have essentially constant slopes.

Figure 10 is a similar recording two days later. Maximum wave heights have fallen to about one-half their values of April 6 although once again there is evidence in the Slope 2 record, but much reduced in amplitude, of a fundamental period similar to that shown in the height recording. The most interesting aspect of these data lies in the extensive high-frequency variations on the height traces. Although this condition is somewhat unusual, it is encouraging to note that the finite interval step recorder gave a record strikingly similar to that of the continuous-wire gage.

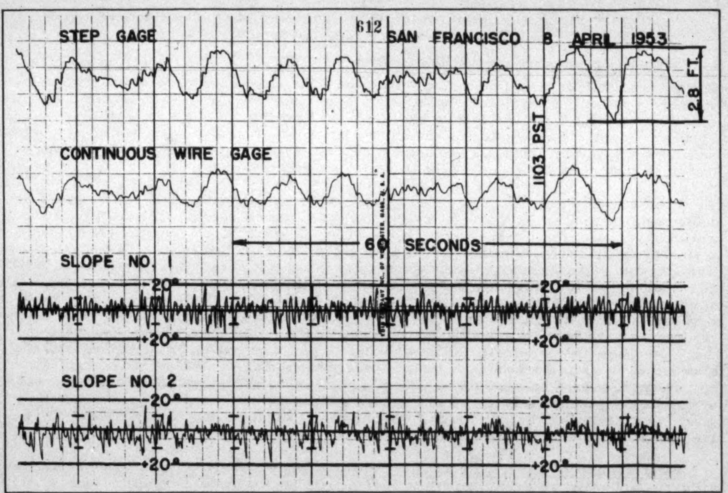

Fig. 10--Section of original simultaneous recording of step- and continuous-wire (height and slope) gage data for April 8, 1953

The data for April 13 given in Figure 11 show relatively small amplitude waves whose slopes, having an estimated average range of about ± 10° from horizontal, are certainly as large as and perhaps larger than those of the previously shown higher amplitude waves. The suggestion here

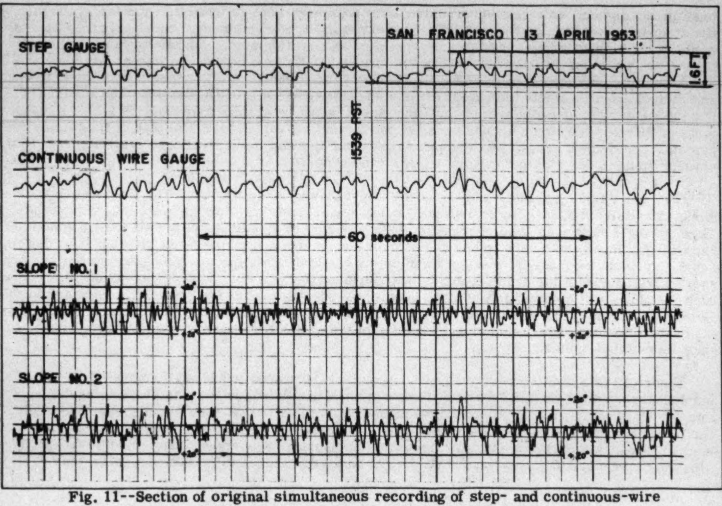

Fig. 11--Section of original simultaneous recording of step- and continuous-wire (height and slope) gage data for April 13, 1953

is that relatively small waves of short wave length are being driven by the wind, and that the sea surface has a definite choppy character. Reference to the observation log for April 13 reveals that wind at the pile at 09h 00m PST averaged 12 mph from WSW, with gusts to 15 mph, a few white caps were observed. In the early afternoon, gusts had increased to 20 mph from WNW at the pile; at Baker's Beach it was definitely too windy for a tethered balloon sounding to be made, and white caps were still visible. Note, too, the much reduced significant period in the amplitude records and the lack of any fundamental periodicity in the slope records.

In the case of the April 14 data (Fig. 12), one can see smaller wind waves superimposed on a larger swell; occasional individual waves of 1.5 to two feet are observed, while swell heights average about two feet. The generally larger slopes observed on the Slope 1 record suggest that the preferred wave direction is more from the direction of Mile Rock than from northwest. Observations recorded in the log show a westerly wind three to five mph at the pile at 09h 15m PST, with no comment regarding white caps, nor regarding the visually observed swell direction. (As a rule, swell approached from the open water with a westerly to northwesterly direction, and the swell wave fronts finally became parallel to the beach. In this respect, the San Francisco Lightship reported an essentially unvarying 270° as the direction from which swell was coming during the entire April observation period.) In statistical terms, one might say that a large RMS value of slope indicates steep-sided waves; simultaneous large amplitude implies long wave length, and vice versa for both. When RMS values of slope are the same for Slope 1 and Slope 2, waves are approaching in the mean from a direction midway between the two legs of the three-wire slope array; when RMS values are significantly larger on Slope 1 than on Slope 2, then waves in the mean are approaching from a direction nearer to Slope 1.

Reduction of wave-gage recordings using height probability distributions--Any discussion or comparison of water-wave sensing devices must also include an evaluation of the methods used in reducing the data and the extent to which the data reduction method gives meaningful and consistent results. Assuming a proper installation, the surface-type gages give a direct and, limited only by the overall response time and amplitude sensitivity of the particular system, an accurate representation of the height variations of the water surface at a given point. As has been shown, this is in contrast to the distorted surface-wave reconstructions obtainable from subsurface sensing-element recordings which result from physical limitations on the response of the sensing element

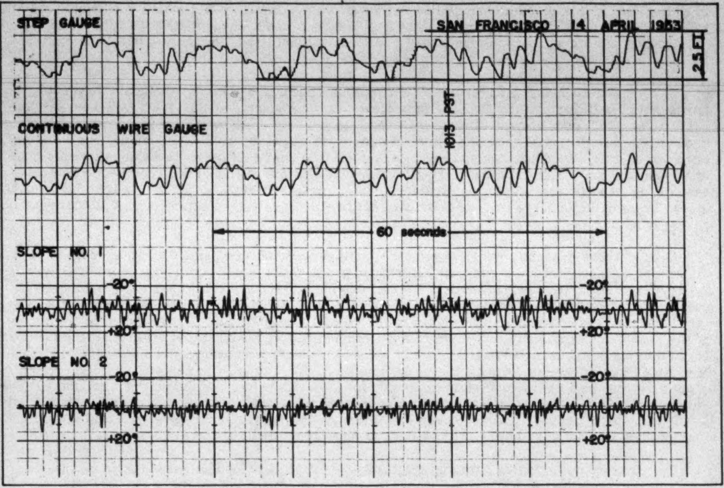

Fig. 12--Section of original simultaneous recording of step- and continuous-wire (height and slope) gage data for April 14, 1953

and the lack of a more comprehensive theory of subsurface pressure recordings. For the time being, however, we lay aside considerations based on the quality of the recordings and investigate the procedures used to reduce the recorded time variations to some meaningful statistics. In this respect, it does not take much of a study to realize that the significant wave method of evaluating a characteristic period and an $H_{1/3}$ is not a satisfactory method of characterizing wave recordings. Both are arbitrarily determined parameters using only the well-defined waves in the recording, and the contributions of the lower short-period waves to the average value are thus ignored. In addition, there is generally an insufficient number of waves in the highest one-third number of waves in a 15- to 20-min observation period to form a good statistical sample. More concisely, it may be stated that the significant wave method was designed to permit the relatively rapid computation of a mean period and height which as a result of using only limited portions of the actual data are only approximations to the true values. The approximations become more valid as the wave recordings exhibit more uniformity in period and height, but uniformity in such recordings is not the normal pattern. In its favor, it should be said that the method is relatively easy to apply to the filtered response of a subsurface pressure sensitive element and is not time-consuming. Its applicability, however, varies directly with the range of frequencies present in the recording, and the mere decision as to what constitutes a wave can be very difficult to make in the unfiltered response of a surface-type sensing element. The desirable alternative to such a method of data reduction involves the evaluation of the mean parameters from complete frequency and height spectra of the wave recordings. While the time required for manual computation of such statistics can seldom be justified, the rapidly increasing development of automatic computing mechanisms now permits the relatively painless and rapid determination of the desired spectra. Certain of the results of such analyses applied to the step-gage recordings will be discussed in the succeeding sections.

If a sufficiently long sample of the recorded continuous time variations of a sensing element is divided into a number of equally-spaced time intervals, each of which is significantly shorter than the minimum period present in the recorded data, and the corresponding amplitudes are plotted against their frequency of occurrence, a height distribution is obtained which can be made arbitrarily close to that represented not only in the original sample but in the actual physical environment being sampled. Since height distributions of water waves have been shown to follow the normal error curve [PIERSON and Others, 1953], it is convenient to plot such distributions on normal error coordinates. In this manner, should the distribution be gaussian, it is a relatively simple matter to determine from the best-fitting straight line, the root-mean-square ($RMS = \sigma$) values of the amplitude fluctuations from the fact that 68 pct (approximately) of the points, that is, from the 16 to 84 pct probability level, are within $\pm 1\sigma$ of the median (50 pct) value.

A series of such analyses for various samples of step-gage data have been carried out by personnel of both the Applied Physics Laboratory and the Electrical Engineering Research Laboratory. At APL, manual evaluation of the height probability distribution has been made using one-second intervals for total sample periods of about four minutes. At EERL, evaluations were made from ten-minute samples using an electronic device and curve following techniques which result in a series of dial readings representing the per cent of time the observed readings were above each of ten fixed (scale) levels. In all cases, chart readings were converted to wave-height values in feet by using an average or representative calibration involving the number of 0.2-ft steps per chart division.

Most of these distributions show essentially linear characteristics. Among the only important exceptions to these linear or gaussian distributions are those which occurred occasionally during the relatively high wave period April 17 to 25. Although there are two factors which could have been responsible for these observed non-gaussian distributions, that is, non-linearity in the step gage itself and the complex oceanography of the channel, a significant part of the effect is felt to be the result of taking samples too short to be representative of the actual water-surface variation. That there was some non-linearity in either the amplifying or recording circuits of the step gage is evident from an examination of the recorded data, that is, full-scale pen motion on the chart might give rise to a calibration shift ranging from seven steps per major chart division at the low end of the chart to nine to ten steps per division at the upper end. However, the effect should only be significant for the very highest waves and, if important, should have shown up on all amplitude distributions made during high wave periods. Such was not the case.

The effect of the complex oceanography is more difficult to evaluate, and it may well have been that the combination of a regular surge-type variation with the normal gaussian distribution of water waves could have given rise to non-gaussian distributions. Since surge effects were apparently present a relatively small per cent of the time, however, their contribution to a non-gaussian distribution is felt to be very limited, and it was not possible to make a one-to-one correlation between surge appearances and the non-gaussian cases. It should be noted in this respect that a series of ten-minute analyses of data samples taken during the high wave period all showed consistent gaussian distributions. However, when the longer analyses were made for the same times at which the four-minute analyses showed serious non-gaussian distributions, the non-linear effects were not eliminated although they were reduced in magnitude. Comparisons of two such distributions are shown in Figures 13 and 14. Thus there can be no doubt as to the reality of an occasional non-gaussian wave amplitude distribution for this location.

An additional step can now be made after obtaining the σ values. PIERSON and Others [1953] have recently shown the following relationships to be valid for a gaussian distribution of wave amplitudes

$$H_{1/3} = 4\sigma$$

$$H_{1/10} = 5.1\sigma$$

One or two observations might well be made. Since the computed points of the amplitude distribution plot exhibit some scatter about a best-fitting line, some judgment is necessary in drawing that line and the resultant slope or σ values may be in error by as much as ± 0.05 or 0.1 ft. The resultant fourfold increase in this value for $H_{1/3}$ is partially reflected in the rather large range of $H_{1/3}$ values that have been found for any one day, although there is no doubt but what the greater part of this variation is real. Great care would certainly have to be taken in choosing a data sample of several minutes duration as being representative of the water surface for periods of several hours even if the mean amplitude were to exhibit no time variation.

Two further comparisons can now be made. Although only some dozen 15- to 20-min samples of step-gage data were analyzed by the significant wave method, it was felt that a comparison of these $H_{1/3}$ values with those computed from corresponding ten-minute samples involving the 4σ relationship might be interesting. Since the Pierson formula for $H_{1/3}$ is equivalent to a definition involving the average height of the highest one-third of all the waves, then one should expect that

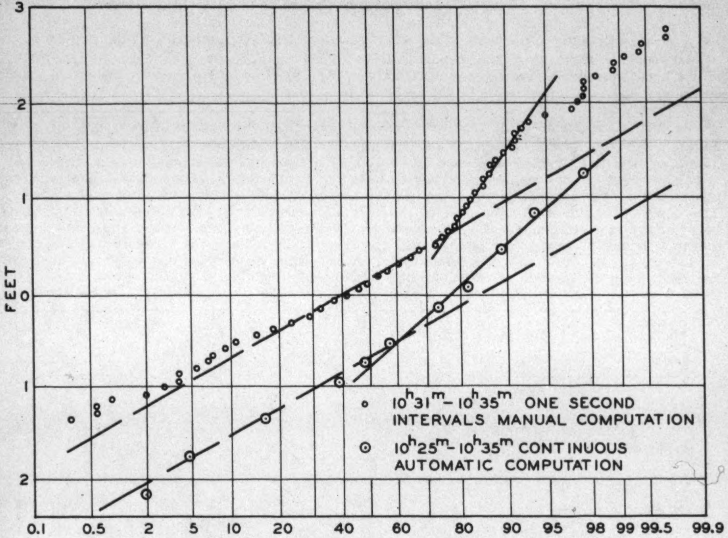

Fig. 13--Step-gage wave data, San Francisco, California, April 22, 1953; comparison of four- and ten-minute sample evaluations of wave height probability distributions showing definite non-gaussian distribution

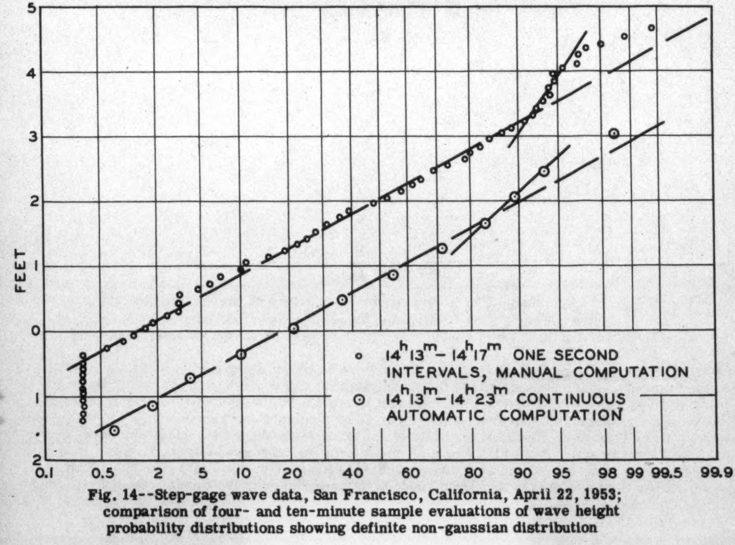

Fig. 14--Step-gage wave data, San Francisco, California, April 22, 1953; comparison of four- and ten-minute sample evaluations of wave height probability distributions showing definite non-gaussian distribution

$H_{1/3}$ values computed on the basis of the significant wave method involving only the well-defined waves should be higher than those computed from the Pierson formula. These data are shown in Table 2 and with the one exception of April 22, the 'significant wave' $H_{1/3}$ values are of the order of ten per cent larger than the values determined from probability distributions.

A final comparison of all pressure-gage and step-gage computations for $H_{1/3}$ is given in Figure 15. No points were used unless both evaluations had been made within no more than ten or 15 min of each other and the step-gage data have been divided into two subdivisions according to the significant wave or amplitude distribution methods of computation. Once again with a very few exceptions, we can see that step-gage values are consistently higher than pressure-gage values. The slopes of the two bracketing lines are 1.12 and 1.52, respectively, and a figure about 1.3 would be a fair average. Once again, too, we note that while the overall range in the two values becomes larger with larger waves, there is a tendency for greater distortion in the pressure-gage readings for low amplitudes. This effect is certainly not unreasonable since waves below a certain critical frequency would be damped out entirely in the pressure sensing unit.

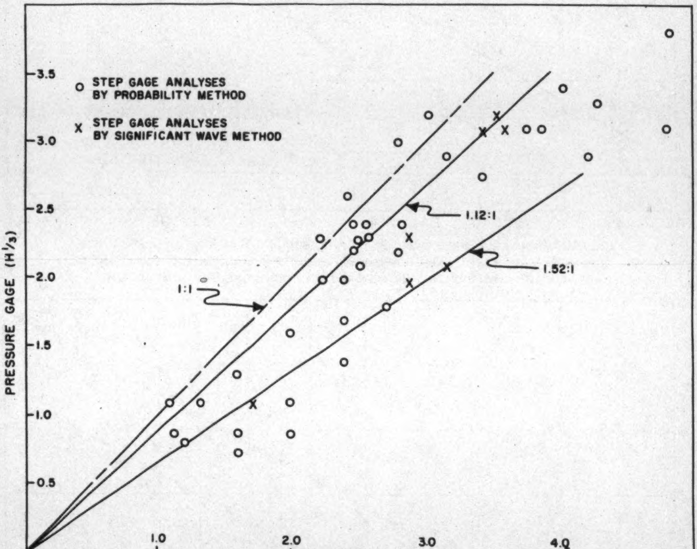

Fig. 15--Summary of $H_{1/3}$ evaluations from step- and pressure-gage data using both height probability and significant wave methods; data taken for ten- to 20-min periods and for times within 15 min of each other

Power spectra comparisons--Since a much more comprehensive analysis of the power spectra of the water-surface variations and of their comparisons with associated radio recordings will be made in a subsequent report, it will be sufficient to state here that there was never any significant discrepancy between either an average wave period or a complete power spectrum for the different wave-sensing elements. An example of this effect is shown in Figure 16, which shows the nearly identical power spectra obtained during a 20-min period on February 19 in which step-, pressure-, and continuous-wire recordings were being made simultaneously. Naturally, the evaluation of a power rather than a frequency spectrum reduces the importance of the higher frequency filtering

Table 2--Comparison of $H_{1/3}$ values obtained by significant wave and probability distribution methods for step-gage data

Date	Time		$H_{1/3}$	
	Significant wave	Probability	Significant wave (1)	Probability (2)
	h m h m	h m h m	ft	ft
April 6	10 41 to 11 01	10 41 to 10 51	3.55	3.04
April 7	13 31 to 13 48	13 32 to 13 42	2.89	2.52
April 8	16 00 to 16 20	16 00 to 16 10	3.17	3.16
April 20	13 51 to 14 08	13 51 to 14 01	2.90	2.88
April 22	10 03 to 10 18	10 03 to 10 13	3.45	4.40
April 22	15 43 to 15 58	15 43 to 15 53	3.60	3.88
April 23	10 16 to 10 32	10 16 to 10 26	2.55	2.48
April 23	15 54 to 16 10	15 54 to 16 04	3.20	2.88
April 24	10 42 to 10 58	10 42 to 10 52	2.41	2.28
April 24	17 05 to 17 25	17 05 to 17 15	2.90	2.24
April 25	11 00 to 11 15	11 00 to 11 10	1.65	1.20
April 25	17 27 to 17 47	17 27 to 17 37	1.71	1.32
Average ratio (1)/(2)			1.04	
Average ratio (1)/(2) omitting April 22			1.12	

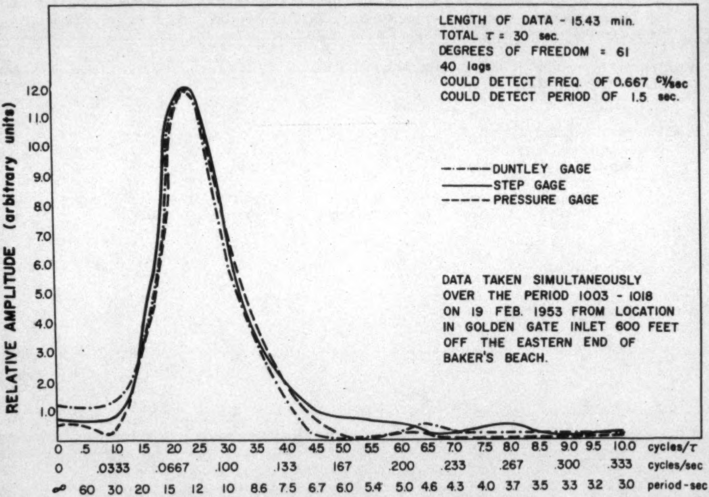

Fig. 16--Representative power spectra for simultaneous 20-min recording of step-, pressure-, and continuous-wire gages

action of the subsurface gage, but it is nevertheless true that the neglect of the high-frequency components and a moderate amplitude distortion has little effect on the power spectrum of a variation having average periods considerably larger than those being filtered.

Acknowledgments--During the measurement program, Frank E. Snodgrass of the University of California at Berkeley gave invaluable assistance in the design and placing of the pile, and he was instrumental in arranging for the loan to us of the Mark IX pressure gage. His cooperation is gratefully acknowledged. This study was carried out under Contracts NOrd 9195, Problem Statement UTX-1-CC-9 and NOrd 7386 with the U. S. Navy Bureau of Ordnance.

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OPERATING CHARACTERISTICS OF AN OCEANOGRAPHIC MODEL OF PUGET SOUND

Maurice Rattray, Jr., and John H. Lincoln

Abstract--The model, constructed to a horizontal scale of 1/40,000 and vertical of 1/1152, is equipped with a tide-producing mechanism and means for adding regulated amounts of fresh and salt water. Tests made include the following: the response of the water level to individual tidal constituents and to typical tides; current patterns throughout tidal periods; and density structure under equilibrium conditions and subsequent to controlled changes in source water. The behavior of the model agrees well with the prototype.

Introduction--A model with a horizontal scale of 1/40,000 and a vertical of 1/1152 has been built as an aid in the oceanographic investigation of Puget Sound. Its small scale and large distortion make it unique among models used to investigate the mechanisms of sea water under inshore and estuarine conditions.

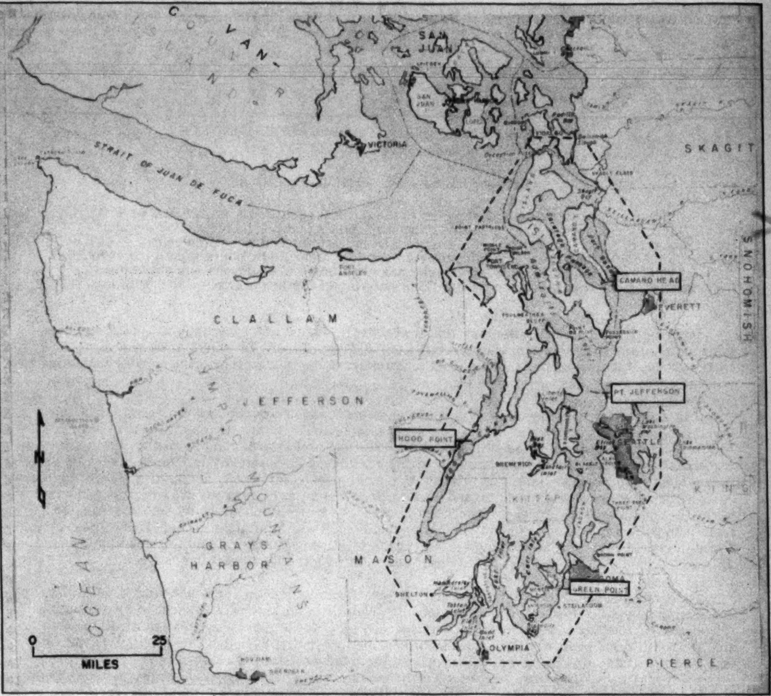
The area under consideration (Fig. 1) extends southward from the eastern terminus of the Strait of Juan de Fuca in a series of arms averaging 34 fm in depth and less than three miles in width. It is divided into four deeper sections by vertical and lateral constrictions. The main basin extends south from a 40-fm threshold sill at the confluence of Admiralty Inlet with the Strait to a 26-fm sill at the Tacoma Narrows. The section south of the Narrows consists of a 100-fm primary basin with many branching channels and inlets. Hood Canal, averaging about two miles wide and having a depth of 100 fm, extends about 50 mi southwest from Admiralty Inlet and is separated from it by a 30-fm sill. The fourth section extends north with diminishing depth from Possession Sound, about 25 mi from the entrance to Admiralty Inlet, through Skagit Bay to Deception Pass. This pass, about 450 ft wide and 16 fm deep, connects with the Strait of Juan de Fuca.

The tides of Puget Sound are of the mixed type characterized by marked differences in the successive heights of low waters. Considerable changes in the tide with respect to character, range, and time occur within the area. Periodically, the tide at Port Townsend loses its mixed characteristics and several days each month becomes virtually diurnal. This effect does not extend into the system for any great distance, and the tides are semi-diurnal over the rest of the system at all times. The tidal range generally becomes progressively greater with distance from the entrance. Port Townsend has a diurnal range of eight feet while the inlets at the southern extremities have 15 ft.

The tidal currents in Puget Sound bear no constant relationship to the tide, either in velocity or time, though in general they increase with increasing tidal ranges. Normally a net outflow exists at the surface, and net inflow at depth. The greatest velocities occur in constricted channels, such as Admiralty Inlet, Tacoma Narrows, and Deception Pass, which have tropic velocities of 4.2, 5.1, and 7.2 knots respectively. The corresponding velocities in the deeper and wider channels are generally less than one knot.

Numerous rivers and small streams feed into Puget Sound from a drainage basin of about 11,300 mi^2, within which precipitation varies locally from 20 to over 100 inches per year. The 11 largest rivers, having a combined yearly runoff of about 40,000 ft^3/sec, account for about 80 pct of the total fresh water influx, the Skagit alone contributing about one-third. The times and magnitudes of peak flows of the rivers are governed by the major water sources. Lowland rivers peak during the winter from rainfall. Those rivers having mountainous areas as their principal watershed peak during the late spring from snow-melt. Others may have both peaks. Hydroelectric developments on some rivers tend to flatten the peaks and maintain a more uniform runoff. Discharges vary greatly, with flow at flood stages being as much as 150 to 200 times the minimum.

Description of model and equipment--The oceanographic characteristics of the area depend in part on the deepness of the waters, particularly in the basins, the strong turbulence over and the depth of the connecting sills, and the small effect of fresh-water runoff. In order to obtain the


VANCOUVER ISLAND
SAN JUAN
VICTORIA
STRAIT OF JUAN DE FUCA
SKAGIT
SNOHOMISH
CAMANO HEAD
EVERETT
CLALLAM
JEFFERSON
OLYMPIC MOUNTAINS
PT. JEFFERSON
HOOD POINT
SEATTLE
BREMERTON
KITSAP
KING
GRAYS HARBOR
MASON
SHELTON
GREEN POINT
STEILACOOM
OLYMPIA
PIERCE
OCEAN
N
0
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MILES

Fig. 1--Area included in Puget Sound model and locations of sampling stations

natural macroscale of turbulence the very rough bathymetry of the region was accurately reproduced by casting the model basin in concrete from accurately contoured hand-carved wood patterns. The model scales chosen are given in Table 1. Further details on model construction and equipment are given in previous reports [BARNES, LINCOLN, and RATTRAY, 1954; LINCOLN, PAQUETTE, and RATTRAY, 1954; PAQUETTE and LINCOLN, 1954].

Table 1--Model scales

Scale	Ratio	Prototype	Model
Horizontal	1/40,000	1 nautical mile 1 mile (statute)	1.82 inches 1.58 inches
Vertical	1/1152	1 foot	0.0104 inch
Velocity	1/34	1 knot	0.60 inch/sec
Time	1/1178	1 hour	3.055 sec
Flow	$1/1.56 \times 10^9$	1000 ft^3/sec	0.067 $inch^3$/min
Salinity	1/2	32 °/oo	16 °/oo

The tide-generating machine is of the Kelvin type employing Scotch yokes and a summation wire which controls the motion of a displacement box. The six constituents included in the machine give a tide within ±1 ft of the predicted prototype tide. They are the diurnal K_1, O_1, and P_1 and the semi-diurnal M_2, S_2, and N_2. In addition, repeating tides can be set up so that any desired daily cycle continuously recurs.

Fresh water is introduced through the 11 major rivers of the system from a constant-head tank. The rates of flow, measured by individual expanding bed type flow meters, are controlled manually. Salt water is continuously circulated between the head box and a salt water reservoir maintained at constant temperature and salinity. A change in ocean or source salinity is accomplished by adjusting the salinity of the reservoir.

The tide heights are recorded with a precision of ±0.002 inch over a range of 0.2 inch by means of a portable gage. Currents are measured photographically from the spacing and position of small vortex rings of dye injected in the desired location at one-second intervals. The salinity is determined to within one per cent by a probing conductivity cell. A permanent conductivity versus depth record is obtained photographically from an oscilloscope trace.

Tide and current--The tidal behavior of the model has been investigated and found to be satisfactory without the use of any artificial roughening. The phase and amplitude changes between Port Townsend and key locations within the Sound were determined for four individual tidal constituents and compared with corresponding values for the prototype (Table 2). Within the main basin, the time lag error was about six minutes (0.3 sec model time) greater than the values of the U. S. Coast and Geodetic Survey. Amplitude ratios agreed with ten per cent. Beyond the constrictions of the Tacoma Narrows and those leading to Bremerton, the deviations were approximately double these values.

Table 2--Comparison of model and prototype tidal behavior

Location	M_2 constituent				S_2 constituent			
	Model		Prototype		Model		Prototype	
	Amplitude ratio	Phase difference degrees	Amplitude ratio	Phase difference degrees	Amplitude ratio	Phase difference degrees	Amplitude ratio	Phase difference degrees
Port Townsend	1.0	0	1.00	0	1.0	0	1.00	0
Seattle	1.4	21	1.57	21	1.7	26	1.57	23
Tacoma	1.5	21	1.68	21	1.8	26	1.66	24
Olympia	2.0	49	2.14	39	2.4	51	2.09	48
Bremerton	1.4	36	1.61	27	1.7	39	1.53	27

Location	K_1 constituent				O_1 constituent			
	Model		Prototype		Model		Prototype	
	Amplitude ratio	Phase difference degrees	Amplitude ratio	Phase difference degrees	Amplitude ratio	Phase difference degrees	Amplitude ratio	Phase difference degrees
Port Townsend	1.0	0	1.00	0	1.0	0	1.00	0
Seattle	1.1	8	1.08	7	1.1	7	1.03	6
Tacoma	1.1	8	1.09	6	1.1	6	1.04	5
Olympia	1.3	16	1.15	16	1.2	14	1.08	14
Bremerton	1.1	14	1.07	11	1.1	10	1.02	9

A marigram of the six constituents for the first half of 1951 at Seattle was drawn by means of the tide machine, using the U. S. Coast and Geodetic Survey constants. The model tides at Seattle for the same period, generated by the tide machine adjusted to produce the correct tides at Port Townsend, were recorded. Portions of the recorded tides were compared with corresponding portions of the prepared marigram and with the tide table predictions (Fig. 2). The average deviation of the recorded tidal heights from the marigram was less than ±0.5 ft. Measurement of the deviation in time lag was not obtained.

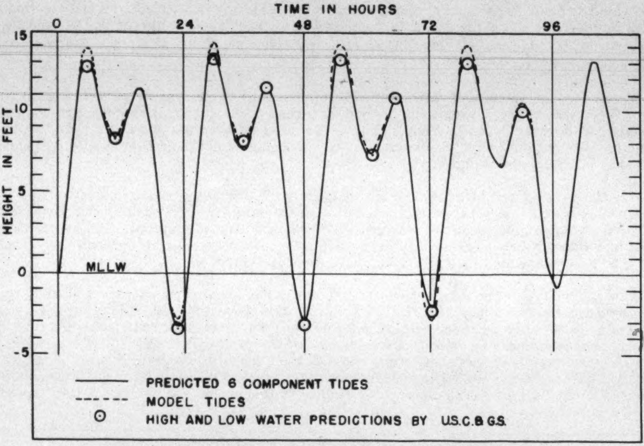

Fig. 2--Comparison of prototype and model tides of Puget Sound, based on six components and corresponding heights of high and low water taken from the U. S. Coast and Geodetic Survey Tide Tables

Horizontal current patterns, investigated by dye movements, are found to be similar to those occurring in nature. Dye has also been used to demonstrate a net inflow from the Strait of Juan de Fuca at depth with a return outflow in the surface layers. Quantitative comparisons of net flow between model and prototype have not been possible because of the difficulty in obtaining adequate field measurements and of correcting for effects of wind and variations in runoff. However, current harmonic constants for the surface layers off Bush Point were compared to those given by the U. S. Coast and Geodetic Survey. The measurements were made during a repeating tide continuously recorded at model Seattle. The ratios of the semi-diurnal current to tide amplitude in model and prototype are respectively 0.58 knot/ft and 0.51 knot/ft. The corresponding phase differences are 63° and 73°. For the diurnal tide the results are 0.25 knot/ft and 0.28 knot/ft respectively for model and prototype with phase differences of 85° in both cases. These results are in excellent agreement considering the different measurement techniques used and the relatively large contribution of the higher harmonics to the current.

Density structure--In the past, most tidal model studies have been concerned with silting in an estuary or harbor rather than the processes involved in and resulting from a variable density structure. Little work on the dynamics of a heterogeneous system resulting from the interchange of oceanic water and river discharge in tidal models has been reported in the literature, and the theoretical requirements for similitude in this respect are not well resolved. It is therefore important to establish the relationship between density structure in the model and the factors by which it is controlled. The density structure in each of the four main sections of Puget Sound was typified by salinity measurements at models Point Jefferson, Camano Head, Green Point, and Hood Point (Fig. 1), under controlled conditions of tide, river runoff, temperature, and source salinity. Repeating tides with average range and diurnal inequality were used throughout these studies. The results of measurements are expressed as prototype values.

The equilibrium salinity structure under conditions of mean river flow is shown in Figure 3 by the curves labeled 'start.' In general, there is a fresher surface layer with sharp gradients to a depth of 30 to 60 ft, below which there is a practically homogeneous, more saline layer extending to the bottom. At first, it might appear that the homogeneous bottom layers were due to a lack of mixing of fresh water down from the surface, but that this is not the case is shown when the salinity of this bottom water is compared with that of the source water. At Point Jefferson and Camano

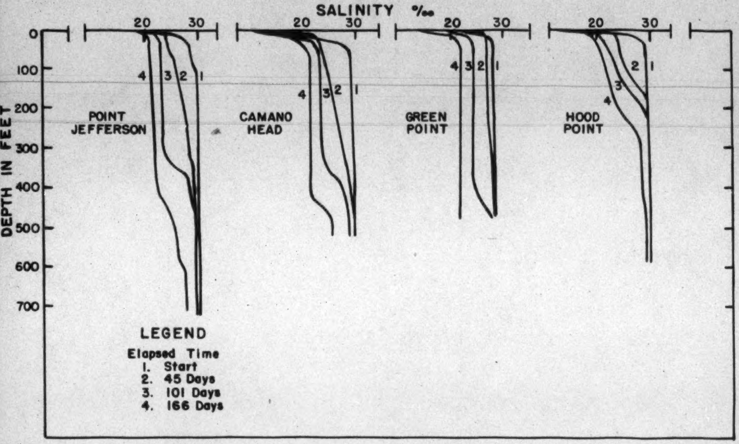

Fig. 3--Change in salinity structure resulting from decrease in source salinity

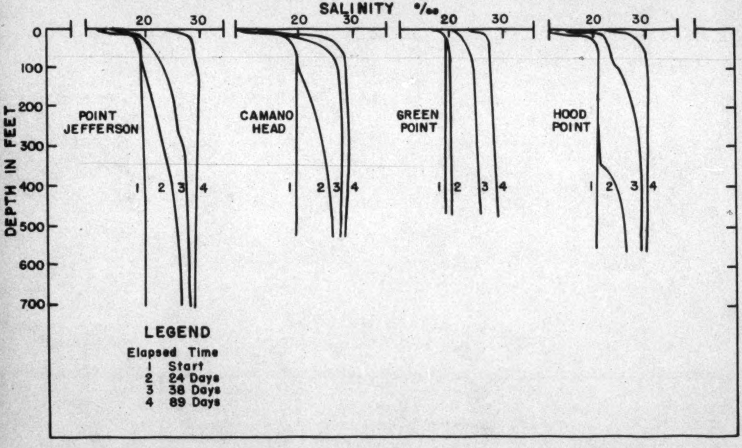

Fig. 4--Change in salinity structure resulting from increase in source salinity

Head the bottom salinities are about 1 ‰ less than the source, while for Green Point the difference is about 1.5 ‰. These differences compare favorably with those found in nature. The mixing in the lower layers must, therefore, be sufficient to destroy any initial gradients in this case. The upper layers have the following features which correspond to those in nature: the layer

N
(a)
(b)
(c)
(d)

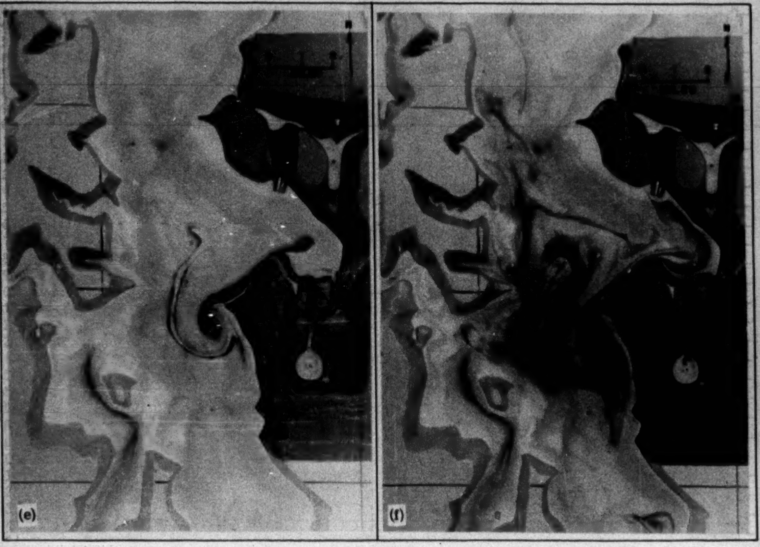

Fig. 5--Dye studies; Duwamish River (see arrow, Fig. 1a) and main basin;
(a) lower high water 10.0 ft, 18.6 hr; (b) lower low water 0.0 ft, 24.8 hr;
(c) lower high water 11.5 ft, 31.0 hr; (d) higher low water 6.0 ft, 37.2 hr;
(e) lower high water 10.0 ft, 43.4 hr; (f) lower high water 10.0 ft, 93.0 hr

depths are within the proper range, and the minimum surface salinity occurs at Camano Head while the surface salinity south of the Narrows is relatively very little less than that in the lower layers. However, under the above conditions, the surface salinities throughout are appreciably less than those found in nature.

A change in river flow causes a noticeable change in the salinity of the model bottom layer within six months south of the Narrows only. Here a salinity change is evident within two weeks for a decrease or two months for an increase in runoff. This is attributed to a combination of several factors: the large tidal exchange, the strong mixing which occurs in that region, and the fact that the source waters are mostly the upper waters of the main basin. At Point Jefferson the salinity of the upper 150 ft reflects the change in salinity of the bottom water south of the Narrows, indicating the Narrows as the source. In all cases, with increase of river flow the upper layer salinity decreases although the relative dilution is less than the relative increase in flow. The depth of the upper layer, however, changes very little with change in flow.

The effect of a change in source salinity was demonstrated by a sudden salinity decrease of 10 $^{0}/oo$ maintained for 166 days and then a return to the original value.

The effect of decreasing the source salinity (Fig. 3) was first noticed at Point Jefferson. A uniform gradient to a model depth of 300 ft developed within 45 days. Subsequent mixing of these waters for a 101-day period produced a homogeneous salinity to this depth, with a sharp interface separating it from the more saline and little affected bottom water. Mixing for a longer period gradually lowered the interface. As would be expected from their proximity and the lack of sill between Camano Head and Point Jefferson, the sequence of events was very similar for the two stations. At Green Point the salinity decrease was later at the surface, but when it did occur it was felt almost to the very bottom. After 166 days the salinity was homogeneous in the bottom

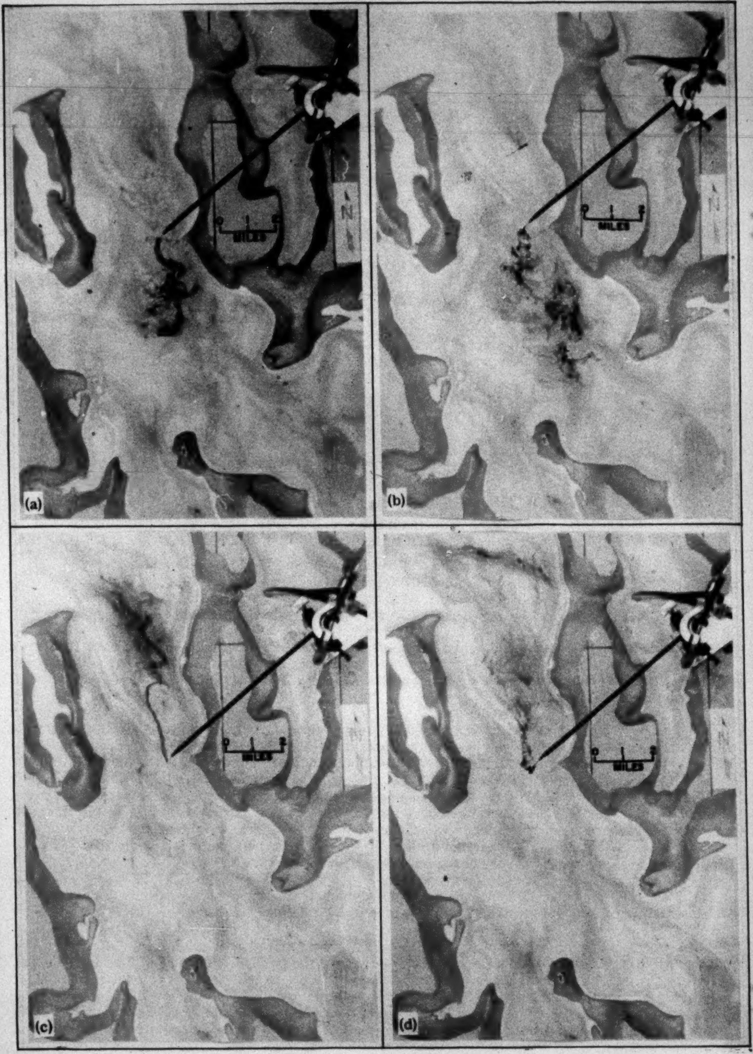

Fig. 6--Dye studies; threshold sill at Admiralty Inlet; (a) 0.7-knot flood; (b) lower high water 10.0 ft; (c) 2.8-knot ebb; (d) lower low water 0.0 ft

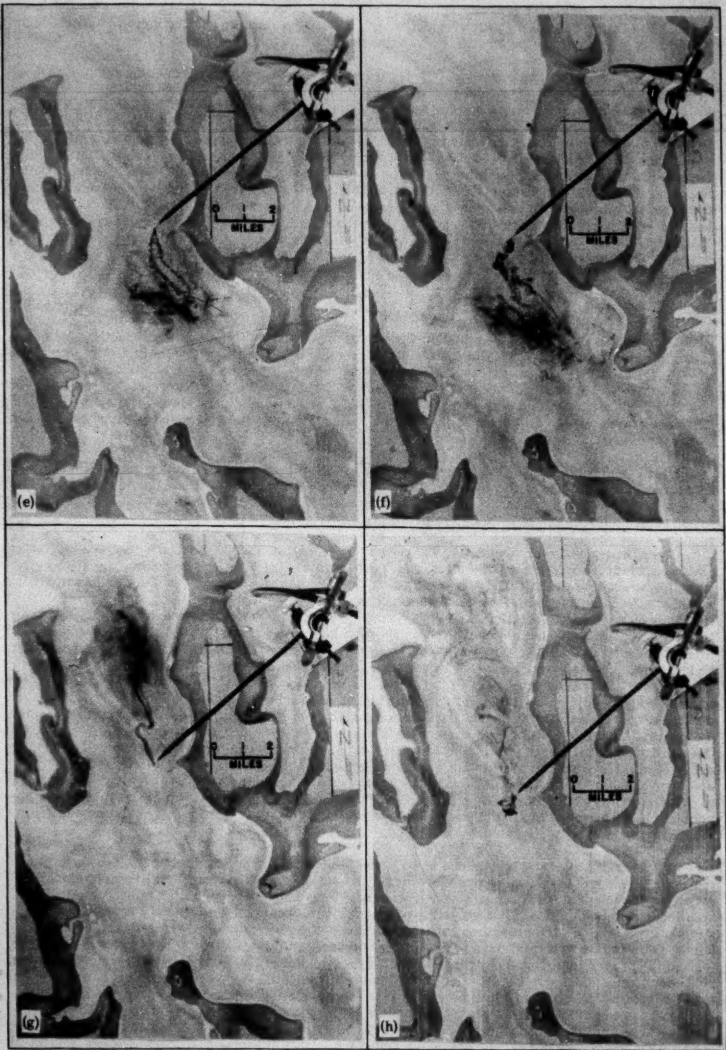

Fig. 6--Dye studies; threshold sill at Admiralty Inlet; (e) 0.7-knot flood; (f) lower high water 10.0 ft; (g) 2.8-knot ebb; (h) lower low water 0.0 ft layer. At Hood Point, the fresher water was noticed only to a depth of 150 ft after 45 days, and to about 210 ft after 166 days, with very little change in the salinity of the bottom waters. Correspondingly, in nature the bottom water in Hood Canal has a tendency to stagnate.

An increase in source salinity produces a series of gradients markedly different from those described above in both shape and rate of change (Fig. 4). Within 24 days there was a considerable increase in salinity of the bottom water at Point Jefferson with the appearance of an almost constant gradient between the depths of 90 and 450 ft. After 38 days the surface gradient was increased to a depth of 150 ft and decreased below that depth. This pattern continued until equilibrium conditions were reached after 89 days. At Camano Head, the salinity structure went through the same sequence, although the mixing appeared to be faster between 35 and 115 ft. At Green Point the increase in salinity was small for the first 24 days; thereafter, a marked increase of salinity occurred at all levels without appreciable gradients below the surface layer. At Hood Point the heavier water appeared to flow into a bottom layer below 300 ft before there was any effect above that level. After 38 days, however, there was more saline water at all depths with a relatively uniform gradient existing between 30 and 240 ft. At this time the salinity below 300 ft had practically attained its maximum value. Equilibrium conditions were closely approached by the end of 89 days.

It is evident from these results that, with the exception of Green Point, significant salinity gradients appear in the model at depths other than the surface for appreciable lengths of times following a change in source salinity, whereas a change in river runoff has only a minor and local effect. Qualitatively these results are borne out in the prototype. Characteristically, the Puget Sound basins flush most rapidly in the fall when the Strait of Juan de Fuca water, the salinity source, is at its greatest annual density and not during periods of maximum local runoff. There is little or no correlation between the mean salinity in the lower layers of the Sound and the amount of fresh water discharge.

Mixing and turbulence--Mixing and turbulence in the model have been investigated qualitatively by means of dye studies with repeating average tides. Two typical examples are presented illustrative of conditions within a basin and those over a sill. Wind and other non-scaled factors require interpretation for comparison with the prototype.

Commencing at lower low water, Congo-red dye solution was continuously injected one-half mile upstream from the model mouth of the West Waterway of the Duwamish River and its movement followed photographically (Fig. 5). After 18.6 hr, at lower high water, the dye has progressed about a mile past the mouth in a northwesterly direction. The dye comes out of the river mouth in the form of a jet on the ebb tide, and then on the flood it is pushed toward the west. At the following lower low water, a second cloud of dye can be seen off the river mouth, while the first has now mainly rounded the point to move in a southwesterly direction. Some of the latter, however, has gone in the opposite or northeasterly direction. During the succeeding flood, the rate of southwesterly flow increases past Alki Point, the western land extremity, where it takes part in a gyre or back eddy set up behind the point. Some additional movement is also noticed in the northeast direction. Since leaving the river, the dye has maintained its identity with little mixing. However, by the next higher low water, the horizontal mixing caused by Alki Point is evident. After the flood, the pattern of mixing in the back eddy is shown more clearly. The line of dye is wound around itself in eddies formed by the current flow past the point. After a total of 93.0 hr this mechanism has spread the major portion of the dye throughout a region about five miles square. A few wisps of dye are evident both to the north and south. The action shown around Alki Point illustrates the primary mechanism of mixing of the surface water in the basins of the Puget Sound model. It is mostly horizontal with only small vertical components.

At Admiralty Inlet the turbulence is so strong that injected dye is rapidly spread throughout the whole area preventing later dye movements from being readily observed. It was therefore necessary to use a starch-iodine solution adjusted to fade at an appropriate rate. The colored solution was introduced continuously at a position 3/4 mi west of Bush Point. Photographs of the dye patterns (Fig. 6) are presented for approximately the strengths of current and slack waters during two similar half tidal days. The similarity between (a) and (e), (b) and (f), (c) and (g), and (d) and (h) is striking, especially since their timing was not exact. Not only is the current pattern reproduced on successive tidal cycles, but also the turbulent pattern apparently repeats. The very rapid mixing which occurs in this region is then due to current fluctuations which are at least in large part predictable. Direct measurements in both model and prototype verify that these fluctuations are similar on consecutive days. On the other hand, the patterns are considerably different at different stages of the current cycle, indicating that the fluctuations are strongly dependent upon the mean tidal current. In contrast to the mixing in the surface layers of the basins, that over the sills is both horizontal and vertical and results in a dilution of the salt water that flows inward to the Sound. This process is one of the most important in controlling the circulation in the system.

Summary and conclusions--An oceanographic model of Puget Sound has been built and subjected to a number of tests to determine its operating characteristics. Results in the model are found to agree well with those in the prototype with the exception that the salinity of the surface layer is too low. This agreement can be attributed to the fact that the major turbulent mixing and friction effects in nature, which occur over the sills, are well reproduced in the model. Not only is the model flow turbulent here, but this turbulence is apparently initiated and controlled by the large scale roughness elements which are accurately modeled. The disagreement in the surface salinities indicates that they do not depend mainly on these factors. Most probably a proper wind effect will in part correct this discrepancy. It is planned to explore this possibility further. Other nonscalable factors such as surface tension and Coriolis force may act to limit the representation of the prototype by this model, but their effects have not been evaluated.

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MICROSEISM AND OCEAN WAVE STUDIES ON GUAM

J. E. Dinger and G. H. Fisher

Abstract--Simultaneous operation of ocean wave gages and seismographs on the island of Guam from July, 1952, to February, 1953, provided data for studying the correlation between waves and microseisms. The use of a wave gage on the east and another on the west side of the island made it possible to record waves incident from opposite directions and thus to determine whether an area of wave interference existed in the water areas around the island. The results of these data can be summarized as follows: (1) large microseisms were recorded when higher than normal waves of about the same period were incident on the east and the west; (2) wave activity well above normal on only one side of the island was not accompanied by any marked increase in microseisms; (3) where higher than normal waves were incident on both sides of the island but where the wave periods had a ratio of 0.75 or less, little increased microseismic activity resulted; (4) when both high waves and microseisms existed, the period of the microseisms was close to one-half that of the wave periods; and (5) an intense typhoon 800 mi distant produced no microseisms. From these observations one may conclude that strong support is given to Longuet-Higgins' theory of microseismic generation by interfering wave trains. Interfering waves generated by two independent areas of wind gave rise to particularly high microseismic activity. The attenuation of microseismic transmission over ocean areas appeared to be high.

Introduction--The literature contains many reports of studies concerning the origin, type of wave motion, and propagation of microseisms as indicated by the bibliography of GUTENBERG and ANDREWS [1952]. These studies present many conflicting viewpoints particularly in regard to the exact nature of the mechanism for the generation of the microseisms. There is, however, general agreement on the following two factors: (1) the generation of microseisms is associated with atmospheric disturbances, and (2) these disturbances must be over a fairly large body of water. The mechanism whereby energy from the atmospheric disturbance is introduced into the Earth as ground vibrations and the subsequent recording of these vibrations by seismographs undoubtedly involve many factors which can be different for each microseismic storm. These variables encompass meteorological, oceanographic, and geological factors. Some of these factors which various authors have introduced and have given varying degrees of importance are: types of atmospheric disturbances such as fronts, lows, and tropical storms; parameters of the disturbance such as wind speed and direction, vertical air turbulence, area, and translational velocity; oceanographic considerations such as depth of water under disturbance, general state of the sea surface and nature of the coast line which may be involved; and geological properties of the ocean floor under the disturbance and of the Earth between the generating area of the microseisms and the seismograph. When consideration is given to the number of possible variables and the large area of the world which can be involved, the difficulty of obtaining sufficient data to permit an unambiguous interpretation is apparent.

Studies reported by KAMMER and DINGER [1950, 1951ab, 1952] and KAMMER [1952] have been concerned with microseisms associated with hurricanes and typhoons and had as an objective the determination of the utility of microseisms for detection and tracking of tropical storms. These studies have led to the interpretation that wind-generated waves enter into the coupling of energy from the atmosphere to the ground vibrations. The experiments and data presented below are a continuation of the effort to determine the mechanism of microseismic generation.

Experimental--Three wave gages were installed on Guam by the Institute of Engineering Research of the University of California as reported by HALL and WIEGEL [1953] and SNODGRASS [1953]. The locations of these three gages are shown in Figure 1 and are designated as Orote, Ylig, and Tarague. These locations were chosen to give exposure by at least one gage to waves from any direction. The gages were of the pressure-sensitive type, and the sensing element was located approximately 150 yd beyond the reef on a heavy steel tripod about 20 ft in height. The feet of the tripod were anchored in concrete on the coral bottom. The water depth was such as to place the sensing element about 20 ft below the mean surface of the water. The signal from each sensing element was transmitted by telephone lines to the central recording location shown on

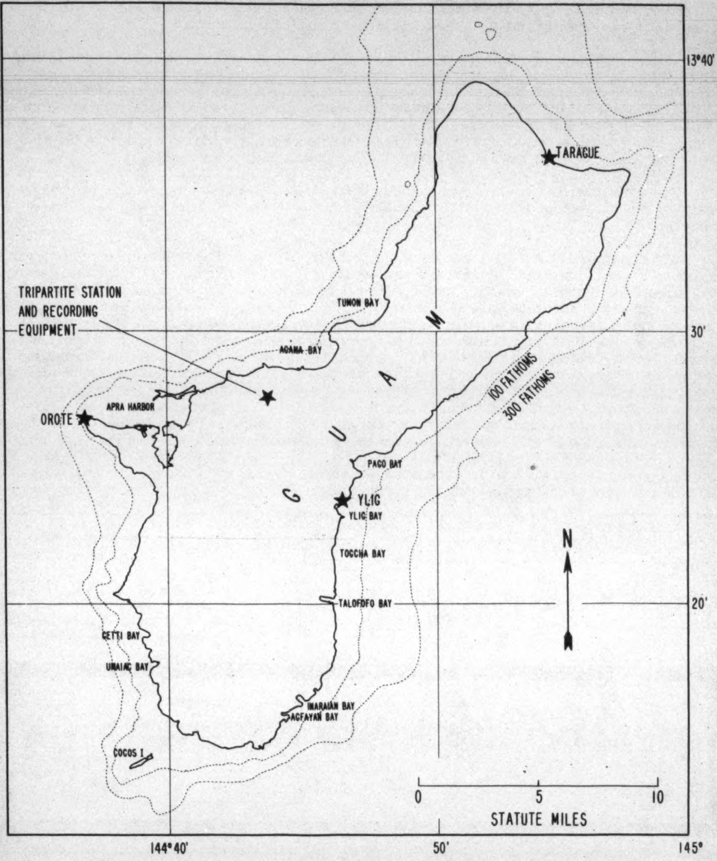
13°40'
TARAGUE
TRIPARTITE STATION AND RECORDING EQUIPMENT
TUMON BAY
30'
AGANA BAY
G U A M
100 FATHOMS
300 FATHOMS
APRA HARBOR
OROTE
PAGO BAY
YLIG
YLIG BAY
N
TOGCHA BAY
TALOFOFO BAY
20'
CETTI BAY
UMAIAC BAY
INARAJAN BAY
AGFAYAN BAY
COCOS I
0
5
10
STATUTE MILES
144°40'
50'
145°

Fig. 1--Map of Guam showing locations of wave and microseism recorders

Figure 1. The signal was recorded on an Esterline-Angus ink-on-paper recorder. The recorder was programed to give a 20-min record every six hours with a chart speed of 1.5 inch/min.

Naval Research Laboratory personnel installed seismic equipment which included a seismograph for continuous monitoring of microseismic activity. This seismograph consisted of a velocity-sensitive horizontal-component seismometer, an electronic amplifier, and a General Electric photoelectric ink-on-paper recorder. The chart speed was 1.5 inch/min.

Seismic equipment was also operated by the Fleet Weather Central. This equipment consisted of a tripartite station. Each seismograph was of the Galitzin type utilizing galvanometer deflections to reflect light on photographic paper carried on a rotating drum. The Naval Research Laboratory equipment was located adjacent to the Fleet Weather Central equipment.

Records obtained and methods of analysis--The wave gage at Orote began operation in July, 1952, Ylig and Tarague in August. These gages were all in operation more or less continuously until December when the Ylig and Tarague gages ceased to function. In general, the Tarague and Ylig gages gave records which were similar. These two gages were both exposed to waves incident from the east, and only in the case of waves from the north or south would one gage be exposed to waves not incident on the other. For the most part, the waves appeared to come from the east or west; therefore, in this report no data from the Tarague gage have been included.

The wave records were analyzed to obtain the so-called significant wave height and period during a 20-min section of the record. The period is the average of three to five well-formed wave groups.

It is recognized that the assignment of one value of wave period to a 20-min record is a rather extreme averaging process. However, if one selects only well-formed groups which are also of the largest amplitude, the scatter in wave period is comparatively small. Since large microseisms are seen to occur only when wave activity is also large, it appears valid to assume that (if waves provide the energy for microseismic generation) the large amplitude waves are of the greatest importance. An effort was made to obtain some measure of the scatter in periods of individual waves about the average period obtained. By measuring the period of 180 individual waves from six typical records it was found that 40 pct of these periods fell within ±0.4 sec of the average for the group, and 70 pct fell within ±1 sec. When one considers that the average periods during the six-month interval varied from 6.5 to 14 sec, it is seen that the scatter within a 20-min interval is small compared to long-term variations. The significant height is the average of the one-third highest waves in the 20-min interval. An appropriate calibration factor for each gage was used to convert the pressure record to height of waves in feet. This analysis was made every 12 hr and for certain days every six hours. Typical wave records are shown in Figure 2; the groups used to obtain an average period are indicated by the brackets.

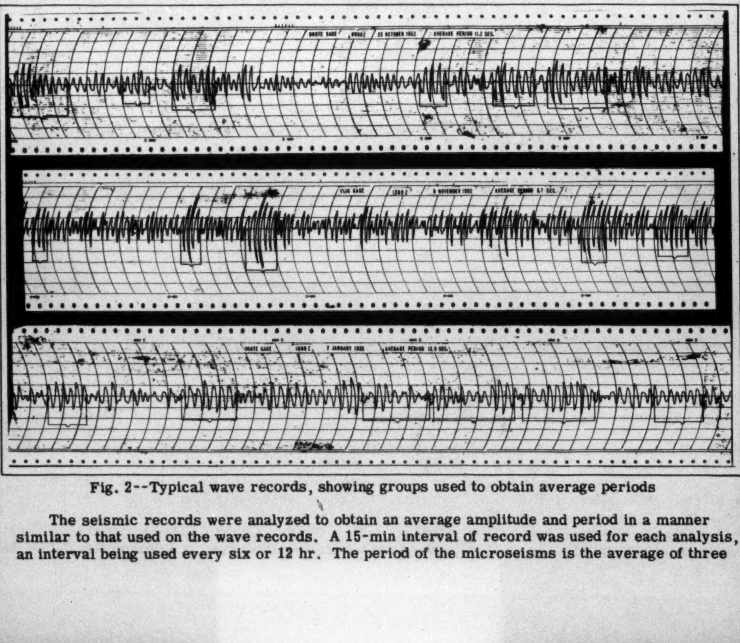

Fig. 2--Typical wave records, showing groups used to obtain average periods

The seismic records were analyzed to obtain an average amplitude and period in a manner similar to that used on the wave records. A 15-min interval of record was used for each analysis, an interval being used every six or 12 hr. The period of the microseisms is the average of three to five well-formed groups and the amplitude in arbitrary units is the average of the 25 largest vibrations in the 15-min interval. This method of obtaining a measure of the relative amplitude was compared with the method used in previous reports, that is, obtaining by a planimeter the area within the envelop of the microseismic record as a measure of amplitude. Comparison of the two methods over the same records extending over a period of five days gave almost identical results. Typical seismograph records are shown in Figure 3. The amplitude of each recording must be increased by the indicated multiplication factors to arrive at the same amplification for all recordings.

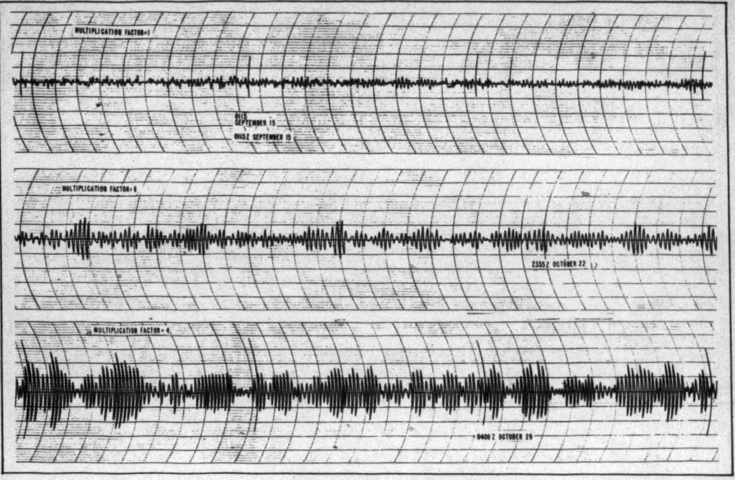

Fig. 3--Typical seismograph records

From October 7 to 22 and December 14 to February 7, the NRL seismograph was not in operation owing to the absence of NRL personnel. During these intervals the amplitude and period of the microseismic data used in this report were furnished by the Fleet Weather Central from their seismograph installation. A conversion factor for reducing the data from the NRL and Fleet Weather Central seismographs to a common arbitrary unit was obtained by comparing data simultaneously recorded over a period of several days.

Presentation of data--In Figure 4 the paths of five of the most interesting typhoons which occurred in the Pacific area during the last half of 1952 are presented. The solid line gives the best track of the storm as determined by the Fleet Weather Central at Guam, this determination being largely based on aircraft reconnaissance. The open circles opposite the dates along the track give the positions of the storm at 12h 00m GMT on that particular day. The solid circles between dates is the position at 24h 00m GMT.

The perpendicular distance between the solid line showing the storm track and the dotted line above or to the right of the solid line is proportional to the center wind intensity at that particular time. The maximum wind intensity for each storm is indicated near the portion of the track where the maximum wind occurred.

The perpendicular distance between the solid line and the dashed line below or to the left of the solid line is proportional to the amplitude of the microseisms as recorded on Guam.

Relation between waves and microseisms--Without consideration of the generating sources of the waves, Figures 5 and 6 show in general a simultaneous increase of wave activity above the normal background and increased microseisms. During September 11 to 18 (Fig. 5), above normal

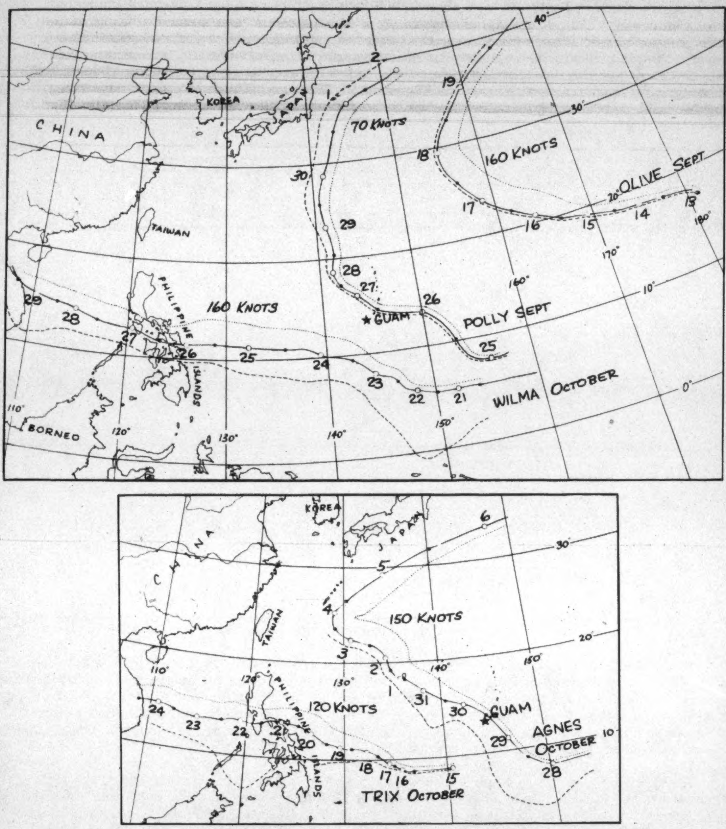
CHINA
KOREA
JAPAN
TAIWAN
PHILIPPINE ISLANDS
BORNEO
GUAM
70 KNOTS
160 KNOTS
OLIVE SEPT
POLLY SEPT
WILMA OCTOBER
150 KNOTS
120 KNOTS
AGNES OCTOBER
TRIX OCTOBER
40°
30°
20°
10°
0°
110°
120°
130°
140°
150°
160°
170°
180°

Fig. 4--Paths of five Pacific typhoons; dashed and dotted lines represent microseism and wind intensity

waves were incident on the east but the waves on the west were low. In view of the fact that the periods of the waves on the east were relatively short, one may conclude that these waves were of local origin. During this interval of waves on the east and very low waves on the west, the microseisms were at a low level.

On September 27 to 29 (Fig. 5), well above normal waves were incident on the east and low waves incident on the west. Microseisms were also low. On September 29, wave activity increased markedly on the west as the waves decreased only slightly on the east. The microseisms also show a marked increase as the waves increased on the west; and during the subsequent interval of September 30 to October 2, microseisms remained at the level of four to five times above background as waves well above background were incident on both sides. During this interval of waves and

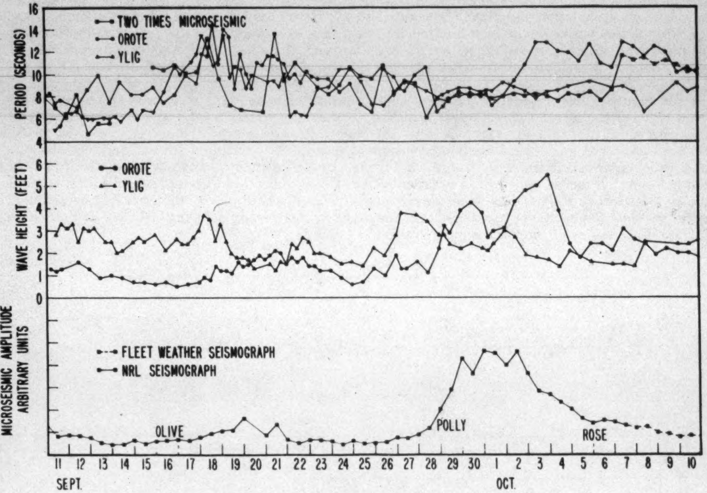

Fig. 5--Microseism and wave characteristics during typhoons Olive, Polly, and Rose; microseism periods have been doubled

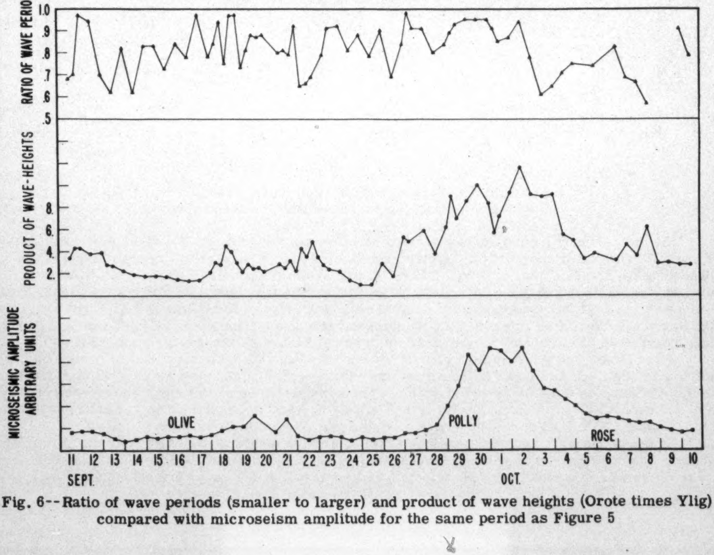

Fig. 6--Ratio of wave periods (smaller to larger) and product of wave heights (Orote times Ylig) compared with microseism amplitude for the same period as Figure 5 microseisms, it can be seen in the top graph that the periods of the waves on both sides of the island were closely the same and about equal to two times the periods of the microseisms. On October 3, the waves on the east continued to decrease somewhat, but the difference in periods of the waves on the east and west became pronounced. The decline in microseisms which began on October 3, therefore, occurred at a time when the periods became divergent.

In Figure 6, the product of the wave heights becomes large only when waves are incident on both sides of the island. Comparison with the ratio of the periods of the waves shows that the microseisms increased in amplitude when the following two conditions were met: (1) the product of the waves from opposite directions increased, and (2) the periods of the waves from opposite directions approached the same value. If only one of the conditions was satisfied, the microseisms did not show an increase. The correlation between the product of waves incident on the two sides of the island when the periods were approximately equal, together with the observation of the 2:1 ratio between the period of waves and microseisms, gives strong support to LONGUET-HIGGINS' [1950, 1953] theory of microseism generation.

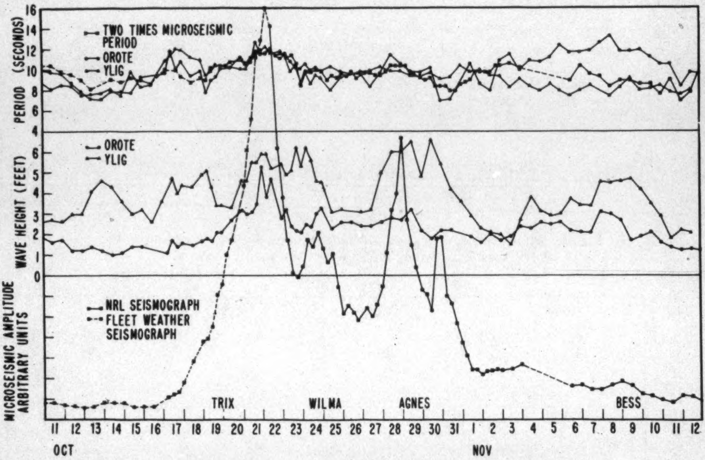

Fig. 7--Microseism and wave characteristics during typhoons Trix, Wilma, Agnes, and Bess; microseism periods have been doubled

The most interesting data which were obtained during the series of typhoons are shown in Figure 7. The important points to be emphasized offer further support to the conclusion of the preceding paragraph. Data of October 11 to 16 give another example of waves well above background level on the east at a time of low waves on the west with resultant low microseisms. From October 17 to 21, the waves increased decidedly on both sides of the island and with periods closely the same. This build-up in waves on both sides occurred at a time when the microseismic amplitude reached an all-time high for records obtained on Guam. As the waves dropped off on the west side of the island, the microseisms also decreased, although the wave level and microseisms still were quite high. On October 27, the waves again increased, accompanied by another high maximum in microseisms on October 28 and 29. The decrease in waves from October 31 to November 2 to more normal values was accompanied by a decrease in microseisms. During the entire interval from October 17 to November 1 of high waves and microseisms, the periods of the waves on both sides of the island were remarkably close to two times the period of the microseisms. From November 4 to 10, waves of above background level were incident on both sides of the island, but a large difference in periods existed. During this time the microseisms were near background level.

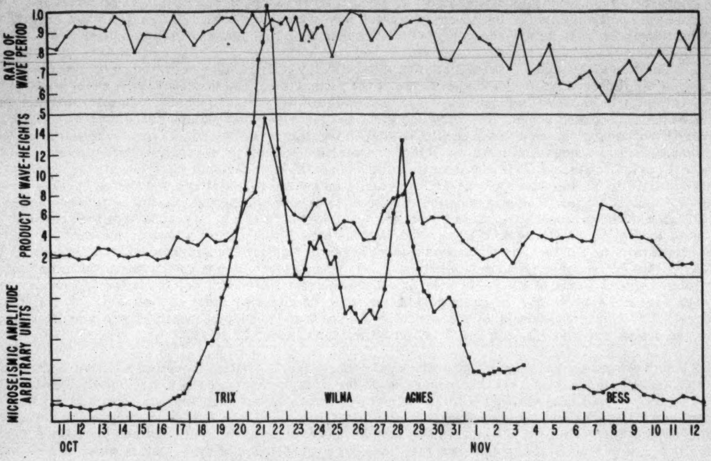

Fig. 8--Ratio of wave periods (smaller to larger) and product of wave heights (Orote times Ylig) compared with microseism amplitude for the same period as Figure 7

Figure 8 shows the comparison of microseisms and the product of the wave heights over the same interval of time as covered in Figure 7. The general shapes of the product graph and the microseismic amplitude graph are strikingly similar. The greatest departure in similarity between the two graphs occurred on November 7 to 10, but this was at a time when the difference in periods of the water waves was pronounced as is indicated by a ratio of periods as low as 0.58 on November 8.

Relation between waves, microseisms, and the location of typhoons--The discussion thus far has been concerned with the correlation between waves and microseisms and has given no consideration to the location of the winds generating the waves.

In general, waves from the east run somewhat higher than waves from the west at Guam because of the easterly trades. As we have seen in the previous paragraphs, when waves were incident on both sides of the island and met certain requirements, microseisms were recorded. The source of these waves may be winds associated with typhoons, the prevailing trade winds, or circulations around high or low areas. Because exceedingly high winds are associated with typhoons, one may expect the resulting high waves to generate microseisms if, as we have seen, an area of interfering waves is established near the island.

Typhoon Olive presents an interesting case in that the microseismic level remained low throughout the storm. Waves incident on the west of the island were also at a low background. Most of the wave action on the east can be attributed to local winds because the period of the waves was short (Fig. 5). We observe, however, that on September 18 and 19 low-amplitude waves of 14 to 16 sec existed. These waves were of rather low amplitude, and similarly, the long-period microseisms show only slight increase in amplitude. It is also of interest that isolated trains of waves of 14- to 16-sec periods could be identified in the wave records on September 13 before Olive had been placed on the weather map. It is possible that this storm existed undetected for several days during her incipient stages and generated waves having long-period components which eventually reached Guam.

Typhoon Polly (Fig. 5) followed a pattern similar to that shown by several other typhoons not discussed in this paper insofar as the waves incident on Guam and the resultant microseisms were concerned. Throughout the entire interval of the storm, waves ran moderately high on the east, most likely from winds not associated with Polly. As the typhoon moved to the northwest and winds from the southwest side of the storm generated waves traveling toward Guam, the wave activity increased at the west side of the island with a corresponding increase in microseisms.

The three typhoons, Trix, Wilma, and Agnes, followed in rapid succession so that waves from two of the typhoons were incident on Guam at the same time. The locations, intensities, and timing of these typhoons were such as to provide the two intervals of exceptionally high microseisms that have been discussed above. To follow the wave and microseismic picture associated with these three typhoons, Figures 4 and 7 should be studied together. On October 15 to 17, the waves on the west were at a background level while those on the east were of moderately high amplitude but of short period. Although Trix was generating to the south, microseisms were low at this time. On October 18 to 20, the waves on the west gradually increased in amplitude and period as Trix moved to the west of Guam. The waves on the east show an increasing period starting about October 18. Wilma was in her generating stage to the southeast at this time and may have been the source of these longer period waves on the east. During this time of increasing waves on the west and continued waves on the east the microseism level began to rise toward a high level. On October 21 to 22, Wilma had reached typhoon intensity and Trix was passing over the Philippines, after having attained center winds of 120 knots. Guam was therefore situated between these two typhoons, and high waves of very nearly the same periods were incident on both sides of the island. The all-time high level of microseisms is very apparent in Figure 7 and is also shown in Figure 4 as the bulge in the dashed lines on the paths of Trix and Wilma for October 20 to 23.

As Trix crossed the South China Sea on October 22 to 24, Wilma moved to the west-southwest of Guam, and the waves decreased somewhat on the west but continued at a moderately high level. The microseisms also dropped from the very high maximum but still continued at a high level. On October 28, the waves on the east increased markedly in amplitude with an accompanying abrupt increase in microseisms. At this time Agnes was generating to the southeast and probably accounts for the rise in waves on the east. We therefore have a repetition of the situation which had prevailed about a week before. Wilma had just crossed the Philippines and waves from her wake were incident on the west of Guam as Agnes generated on the east with resultant high waves from the east. The microseisms associated with this interval had the second highest amplitude recorded on Guam.

It is important to point out that throughout the interval of high waves and microseisms resulting from these three typhoons the periods of the waves incident on the east and west of the island were closely equal to twice the microseismic periods.

As Agnes dissipated south and east of the Japanese Islands on November 4 to 6, long-period waves continued to be recorded on the west of Guam, the wake apparently continuing until November 9 or 10. During the incipient stages of Bess to the east, fairly high waves of short periods were recorded at the east gage. This situation provided one of the several examples of considerable wave activity on both sides of the island but where comparatively little microseismic activity resulted. It seems significant, therefore, to point out the wide difference in the periods of the waves as recorded on the two sides of the island and to emphasize again how this condition fits in with Longuet-Higgins' theory. Very little microseismic activity occurred throughout the time Bess was in existence, even though center wind intensity reached a velocity of 100 knots between Guam and the Philippines.

Relation between microseisms and typhoon intensity, distance, and other factors--A qualitative correlation (or lack of correlation) between microseismic amplitude and the center wind intensity can be observed by a study of Figure 4. The rise and fall in microseisms appears to be independent of the rise and fall in center wind intensities and in a number of cases shows just the opposite relation that one would expect if the source of microseisms were associated with the center of the storm. Agnes is an outstanding example of negative correlation. On October 28, microseisms were at a high level while the center wind intensity was low. On October 29, as the distance from the storm to Guam decreased and as the center wind intensity increased, the microseisms decreased. After the storm passed to the northwest on October 31, the microseisms showed a steady decrease as a steady increase in center winds occurred. Other examples of decreasing microseisms at times of increasing wind intensities are apparent. There are cases, such as during Polly, when a good correlation appeared to exist between wind intensity and microseisms. However, the microseisms and wave activity recorded present a consistent picture for a period of several months, and it is believed that any short intervals of positive or negative correlation between wind intensity and microseisms are coincidental and have little significance.

Discussion--LONGUET-HIGGINS [1953] has discussed three situations which may give rise to the standing-wave conditions necessary to produce microseisms in accordance with his theory, namely: (a) a circular depression, (b) a moving cyclone, and (c) reflection from a coast. In the light of this discussion and the investigations reported by DARBYSHIRE [1950] and DEACON [1947], it was at first thought that the observations at Guam could reveal situations when microseisms would be recorded and no local waves would be incident on the island to associate with the microseisms. This situation would arise if the interfering wave region producing the microseisms were in the trail of the typhoon and waves from the typhoon had not as yet reached water areas near Guam, provided also that the microseisms generated near the storm were propagated across the ocean floor without serious attenuation. It, however, appears that the interfering region was within at least a few hours' wave travel of Guam because the rise and fall in microseisms coincided with wave activity when the microseisms and wave records were sampled every six or 12 hr. It is believed, therefore, that the most important situation giving rise to regions of interfering waves in the vicinity of Guam occurred when the waves were generated by two or more independent sources and arrived simultaneously in the vicinity with similar period and nearly opposite directions of travel.

GUTENBERG [1953] has reported data obtained on the West Coast of the United States in which maximum microseismic amplitude was delayed with increasing distance from the storm center, and that in Southern California the maximum microseisms usually coincided with the arrival of highest waves.

It is also worthy of note that the maximum amplitudes as well as the normal background of microseisms at Guam were higher by a factor of two to four than are the microseisms recorded on the East Coast or in the Caribbean. This may result from the fact that Guam is located in an exposed manner with hundreds of miles of ocean on all sides, thus giving ample opportunity for waves from independent sources to produce an interference situation. Along the coast of a continent the opportunity for waves from independent winds to interfere is greatly restricted.

VIGNESS, KAMMER, and DINGER [1952] present a discussion which indicates that the energy transferred to the ocean floor may be greater when the interfering waves are in shallow water than when the waves are over deep water. According to them, in deep water only those waves whose directions are almost exactly opposite will produce a standing wave such that the second-order pressure variation will not be attenuated appreciably before exerting a pressure variation on the ocean bottom. In shallow water, however, a greater spread in the direction spectrum of the interfering waves can be tolerated before attenuation of the second-order pressure variation on the ocean bottom becomes complete. The relation between the microseisms and the conditions which Longuet-Higgins' theory requires to produce microseisms as presented in the above data is more clear-cut than any data previously obtained by the Naval Research Laboratory on the East Coast of the United States or in the Caribbean. One reason for this unambiguity may be due to the fact that the water areas surrounding Guam are very deep; therefore, microseisms are generated only when well-defined standing-wave situations are developed. Evidence that storms over the shallower areas of the Atlantic are more efficient generators of microseisms is reviewed by TEN KATE [1951].

Summary--The data presented and discussed were obtained during two months of the six during which wave gages and seismographs were in operation. All the records obtained supported the interpretation discussed above and can be summarized as follows:

(1) Increased microseismic amplitude was recorded when higher than normal waves of about the same period were incident on the east and west. Good correlation was found between microseismic amplitude and the product of wave heights on the east and west when similar periods prevailed.

(2) Wave activity well above normal on only one side of the island was not accompanied by any marked increase in microseisms.

(3) In those cases where higher than normal waves were incident on both sides of the island but where the wave periods had a ratio of about 0.75 or less, little increased microseismic activity resulted.

(4) At those times when both high waves and microseisms existed, the period of the microseisms was close to one-half that of the wave period.

(5) An intense typhoon 800 mi distant produced no increase in microseisms on Guam.

Conclusions--From the data as presented the following conclusions seem reasonable:

(1) Strong experimental support is given to Longuet-Higgins' theory of microseismic generation by interfering wave trains.

(2) Interfering waves generated by two independent areas of wind give rise to particularly high microseismic activity.

(3) The generating area for the microseisms recorded on Guam appears to be within a relatively short radius of the island.

(4) The attenuation of microseisms propagating over ocean areas around Guam appears to be quite high.

Acknowledgments--It is a pleasure to acknowledge support given this work by the Navy Bureau of Aeronautics (MA-5) and the extensive efforts put forth by the Institute of Engineering Research of the University of California to make the wave-gage installation on Guam. Personnel of a number of naval activities have given considerable assistance in arranging and carrying out many details in the installation and operation of the Guam installations. These activities include Bureau of Aeronautics (MA-5), CNO Op533, Office of Naval Research, and the Fleet Weather Central, Guam. Special thanks are extended to the Fleet Weather Central for the use of seismograph records to supplement the Naval Research Laboratory records.

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CURVATURE DISTRIBUTIONS OF WIND-CREATED WATER WAVES

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Abstract--Measurements made using a small water-wind tunnel, having a maximum fetch of 26 inches, indicate that water waves are not formed until the wind velocity reaches approximately seven knots. After this threshold there is a sudden build-up of the waves. Between seven and 20 knots, the mean curvature of the surface c in cm^{-1} is related to the wind velocity v in knots by the expression $c = 0.046v$. The standard deviation σ in cm^{-1} of the curvature is related to the wind velocity by the expression $\sigma = 0.036v - 0.11$. The momental skewness of the curvature distribution was positive and averaged about 0.8 standard deviation unit.

Introduction--The reflection and scattering of light, radio, and sound waves impinging upon a wind-disturbed water surface depend upon the orientation and sizes of the scattering elements. It is therefore desirable to measure the distributions of the sizes and slopes of facets of the sea surface.

COX and MUNK [1954] and SCHOOLEY [1954] have studied the statistical distribution of water surface slopes for various wind velocities by two different methods and are in substantial agreement on this aspect of the problem. The distributions of facet sizes still need to be determined.

In this paper a simple optical method is described for taking data related to the distribution of water facet sizes. The term 'facet size' is really ambiguous because a wind-disturbed water surface has perfectly flat facets only over infinitesimal areas. Thus, there is a need for a more meaningful measure of facet size that includes the concept of how much the various facets deviate from being perfectly flat. It appears that this can be done by measuring the radii-of-curvature of the facets.

Method--Figure 1 is a schematic presentation of the photographic method that has been used for determining the distributions of curvature and radius of curvature of water waves. C represents a camera with film F and lens L directed towards water surface W. The water surface is illuminated by a light source of diameter ℓ_o. The light source is shown co-axial with L indicating that actual parallax between the light source and the lens has been neglected. An image (diameter ℓ_i) of the light source is formed by reflection from the water surface. The camera records an image of diameter ℓ_c on the film F. It can be shown that

$$\ell_c \cong (r\ell_o d_c)/[2d_o(r \pm d_o)] \qquad (1)$$

where

ℓ_c = camera image size
r = radius of curvature of the water facet
ℓ_o = size of illuminating source
d_c = camera lens to film distance
d_o = lens-to-water distance

The second term in the denominator is positive for a convex facet and negative for a concave facet.

The following assumptions were made in deriving (1): (a) the facets may be represented as spherical mirrors having small apertures; (b) the lens-to-water distance is a constant; (c) the lens aperture is small; (d) there is negligible parallax between the light source and the lens; and (e) the light and the lens are at the same distance from the water surface.

The water facet shown in Figure 1 is on the axis of the camera and hence ℓ_c is in the center of the film F. Projected images of facets at angles off the axis will be approximately proportionally displaced from the center of the film if the angles are less than about 20° [SCHOOLEY, 1954].

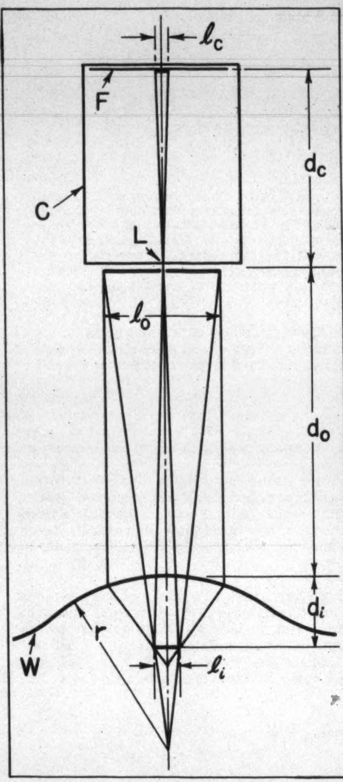

Fig. 1--Geometry for measuring radius of curvature

Figure 2 shows (1) plotted with camera image size ℓ_c as abscissa for the conditions of convex and concave facets. The constants indicated on the figure were used because preliminary experiments had indicated that the region of principal interest was between 0.03 and 0.3 ft radius of curvature. With the constants chosen, the curves for convex and concave facets are substantially the same in the region of interest, and the minimum camera image size is resolvable with readily available photographic equipment.

Apparatus--In order to meet the conditions set forth in the preceding paragraph, the simple water-wind tunnel of Figure 3 was constructed. The clear plastic-walled channel between the two end containers is three inches wide. The water depth is about seven inches. Above the water is an air space of about three inches. Air is drawn from left to right by the two vacuum-cleaner blowers at the upper right. The wind velocity was measured by a Type P Portable Air Meter of the Hasting Instrument Company pictured in the right foreground. The probe for this meter is shown inserted in the airstream and held by the ringstand clamp just behind the water-wind channel. The velocity of the airstream was adjusted by means of a Variac used to control the speed of the blower motors. The waves traveling into the right container were largely absorbed by a screen at its entrance. The photographic equipment (not shown) consisted of a 4 × 5-inch speed Graphic with a six-inch Ektar lens set at f8. A focal plane shutter speed of 1/1000 sec was used. The camera was mounted directly above the center of the channel. The light source was a GE no. 31 flash bulb masked down to 2.25-inch diameter and held adjacent to the camera lens. The slight tilt of the transparent top of the channel shown in Figure 3 was used to throw the reflections from its surfaces outside the field of view of the camera.

Figure 4a shows a picture of the quiet water surface with no wind blowing. The diameter of the center light image corresponds to the right hand flat portion of Figure 2. The other images are due to the curvature of the water at the walls of the channel and may be disregarded. As the wind speed is gradually increased, the central image will remain intact until it suddenly breaks up in the region of seven knots. Figure 4b shows the onset of this breakup. For higher wind velocities, the pictures resemble Figure 4c which was taken at a wind speed of about 11 knots.

Data analysis--Examination of Figures 4b and 4c shows that the images are irregular and not circular. Thus it is evident that the surface is not made up of small portions of many perfect spheres, and the spherical concept is only a first approximation. The images are usually longer across the channel than along the channel. This indicates that the average radius of curvature of the waves is greater when measured across the wind than when measured with the wind. All measurements presented in this paper were made to the outer edges of the facets in the direction of the wind.

About 24 pictures were analyzed by measuring the size of the image of the individual facets for various wind velocities. The maximum widths of the facets were measured in the direction of the wind for a central one degree wide strip extending 10° upwind and 15° downwind. In the water-

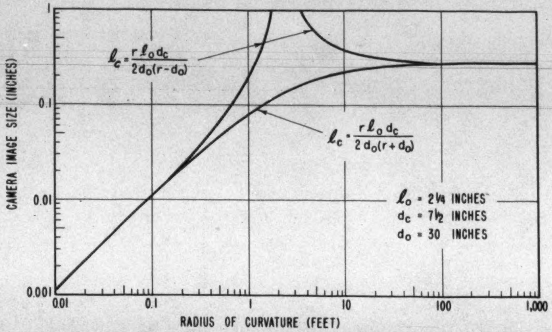

Fig. 2--Relation between radius of curvature and camera image size

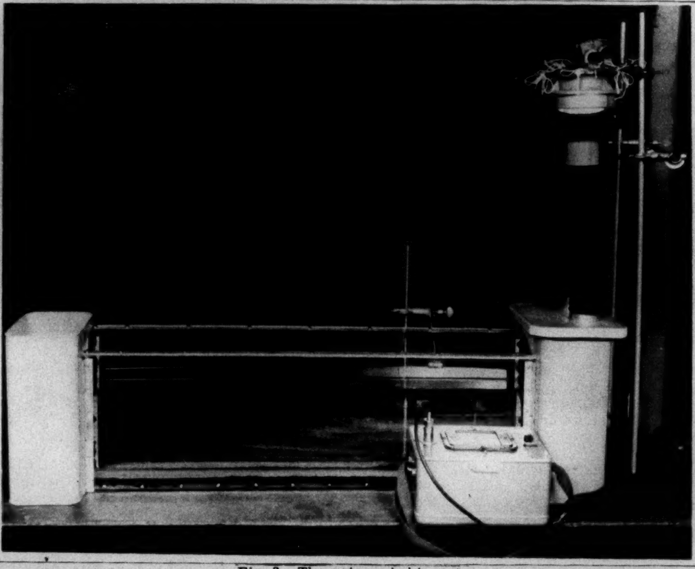

Fig. 3--The water-wind tunnel

wind tunnel used, these limits corresponded to a minimum fetch of about 14 inches and a maximum fetch of about 26 inches. Thus the average fetch was about 20 inches. The image sizes were measured under a low power microscope using suitable reticules. The image sizes were next converted to radii of curvature by means of Figure 2, and made into spot diagrams, one of which is shown in Figure 5. Each spot on this diagram represents the radius of curvature of a facet at a particular

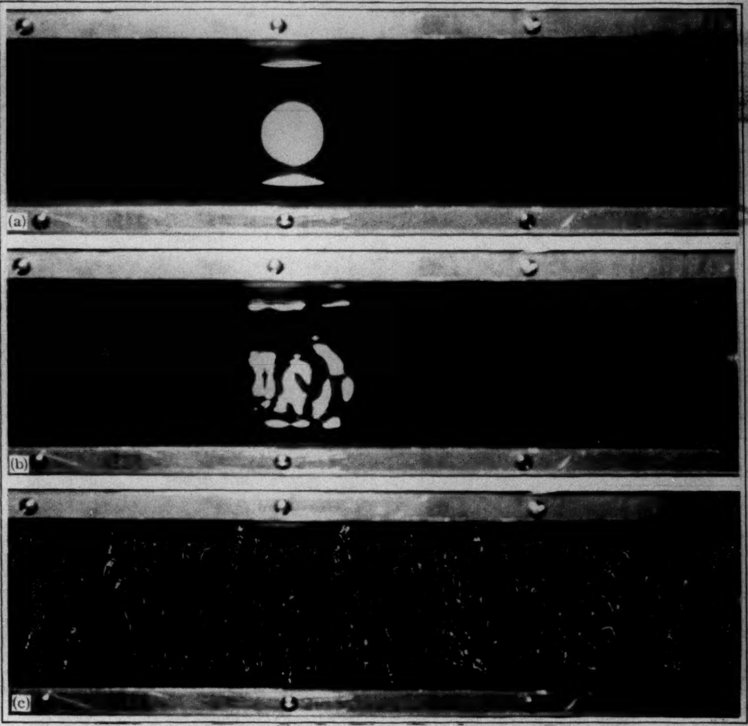

Fig. 4--Water surface (a) with zero velocity wind; (b) with approximately seven-knot wind; and (c) with approximately 11-knot wind

angle which also corresponds to the slope of the facet. An examination of many of these diagrams leads one to believe that the distribution of radii of curvature is substantially the same for all slopes.

The next step in the analysis involved converting radius of curvature to its reciprocal, curvature, and making frequency distributions from the spot diagram data. One of the frequency distributions is shown in Figure 6. The methods of statistics were used to determine the mean curvature, standard deviation, and momental skewness [KENNEY, 1947]. The results of part of this analysis are summarized in Figures 7 and 8.

Discussion--Figure 7 shows that winds of less than a threshold value of velocity do not generate waves on the water surface. The fact that there is a threshold is consistent with the principal theories relating to wind-generated waves [RUSSELL and MACMILLAN, 1953]. However, since there is disagreement among the theories regarding the wind velocity at which the threshold takes place, this part of the experimental curve is of interest. The Kelvin-Helmholtz theory of instability, which assumes laminar flow, predicts that waves should start to appear at a wind velocity of about 13 knots. The sheltering theory of Jeffreys, based on the assumption that the flow is partly laminar

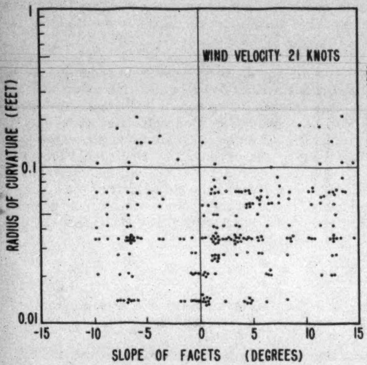

Fig. 5--Distribution of radii of curvature for various facet slopes

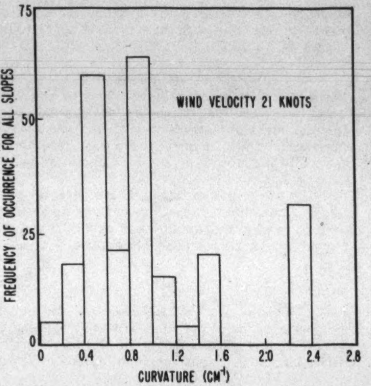

Fig. 6--Frequency distribution of curvature

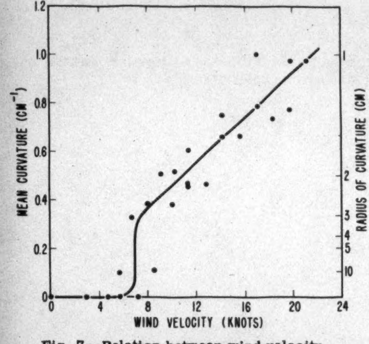

Fig. 7--Relation between wind velocity and mean curvature

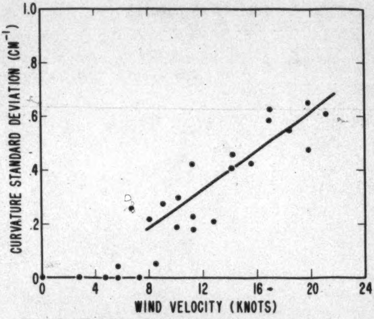

Fig. 8--Relation between wind velocity and curvature standard deviation

and partly turbulent, has been used to explain some observations that a wind speed of as low as about two knots will cause waves to appear on still water. Under the experimental conditions that lead to Figure 7, the critical wave-forming wind velocity appears to be in the region of seven knots. This is about half way between the velocities that are justified by the Jeffreys and by the Kelvin-Helmholtz theories.

The experimental scatter of the points in Figure 7, combined with the lack of adequate theory to help determine what the trend of the data should be, makes it difficult to draw the curve that is shown. The straight-line portion of the curve could have been drawn with a range of slopes and still be reasonably consistent with the small sampling of data. For simplicity, a straight line was selected, which, if projected, would intersect the origin. The equation of this line is $c = 0.046v$, where c is the curvature in cm^{-1} and v is the wind velocity in knots.

In Figure 8 the curvature standard deviation σ is plotted as ordinate with wind velocity as abscissa. The threshold effect is still evident but not in as striking a manner as in Figure 7. The approximate average curve for the data above seven knots still appears to be a straight line. However, its intercept with the σ-axis appears to be less than zero. The equation for the line that is shown is $\sigma = 0.036v - 0.11$.

According to private correspondence with Munk, Neumann's energy spectrum proposed on the basis of amplitude observations may be used to predict a standard deviation or rms value of 0.1 cm^{-1} curvature that is independent of wind speed. It is interesting to note that Figure 8 shows that the curvature standard deviation was not found to be constant for wind velocities above the threshold. The rate of increase was 0.036 cm^{-1}/knot. Figure 8 also indicates that above the threshold the curvature standard deviation is always larger than predicted by Neumann's theory.

The momental skewness of the curvature distributions for various wind velocities was calculated. Above the threshold velocity of about seven knots, the skewness points scattered in a more or less random fashion between about 0.3 and 1.3 standard deviation units. The skewness was consistent in that all points were positive.

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A MODEL STUDY OF WAVE ACTION ON A CYLINDRICAL ISLAND

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Abstract--The heights and phase relationships of non-breaking ocean waves about a cylindrical island were shown by a model study to be in agreement with the corresponding diffraction theory. The variation of pressure with depth, however, was found to be more rapid than the hyperbolic cosine variation which has been used for forces on piling.

Introduction--The current interest in off-shore oil-well drilling has emphasized the lack of available information on the interaction of ocean waves and cylindrical islands. The theory of diffraction of plane waves by a cylinder has proved satisfactory in light and sound and should be expected to predict the behavior of the water surface around such an island. For design purposes the underwater pressure is probably more important than the total wave thrust, and since the details of the diffraction theory have been worked out for infinite depth, it was desired to check the applicability of this theory to cases of finite depth.

The experimental work was to be exploratory. It was desired to test instruments and circuits, to study the phenomena, and to discover areas of agreement with theory.

Theory--The theory of diffraction of plane waves by an infinite cylinder was examined by HAVELOCK [1940], and presented in convenient form by WIENER [1947]. Wiener's tables for pressure variation and phase relations around an infinite cylinder formed the basis for comparison with the experimental values. In the experiment, wave heights and water pressures were measured as functions of time and position. A direct comparison with the theory would require the measurement of the variation of pressure at the water surface. The pressure at the surface, however, is that of the atmosphere above it and is essentially constant. This difficulty can be resolved by assuming that heights above and below the still water level correspond to the pressure variations of the diffraction theory. Since it is known that breaking waves can exert much more pressure on a surface than is represented by the run-up of the water, the assumption of interchangeability of pressure and height must be checked even for non-breaking waves. The check used in this research was the comparison of the theoretical pressures with the photographic measurements of wave height and with the pressures at the surface as extrapolated to zero depth from the variation of oscillating pressures with distance below the surface.

A comparison was also made of the experimental and theoretical phase relationships. In previous work on gravity waves it has been shown [LAMB, 1945, p. 367] that the effects of waves decrease with increasing distance below the surface. Therefore, it was to be expected that a similar trend would obtain in the present study. As a first approximation MacCAMY and FUCHS [1952] suggested multiplying the surface pressures by the factor developed in the potential theory of small gravity waves in water of finite depth which describes the decrease of orbital velocity with distance below the surface. This factor is the ratio of the hyperbolic cosines of the products of the wave number with the distance of the point from the bottom and with the water depth respectively. It was desired to test this hypothesis experimentally.

Equipment--The model was a flat-bottomed three-foot diameter cylinder weighted with iron and centered up in the 58-ft long by 65-ft wide model basin.

Four bridge circuits were built up using Wiancko 3-PAD-10 variable induction type pressure sensitive elements. Each element was connected electrically with two precision resistors to form four-arm bridges. The bridges were connected through isolating transformers and condensers to Brush Electronic Company Universal Analysers and Penmotor oscillographs. The least sensitive but most stable bridge circuit had a transformer primary resistance of 200 ohms with a winding ratio of 0.66. The most sensitive had a primary resistance of 47 ohms with a winding ratio of 0.24 and was used with a 200-ohm resistor in series. The resulting sensitivities were 0.038 and 0.010 ft of water pressure/mm deflection.

The pressure elements were attached inside the cylinder behind 1/16-inch holes drilled through the wall at 4, 8, 12, and 16 inches from the bottom in a vertical line. The still water level in the basin was kept at 1.40 ft; as a result, the top pressure hole was sometimes uncovered in the wave troughs. The variation of pressure around the cylinder was obtained by turning it 180° about its axis in 30° steps.

Calibration of the pressure elements was accomplished by manifolding the elements to a level bottle mounted on a depth gage rack. Cocks were provided to isolate the elements from the basin or from the level bottle. With all cocks open, the oscillographs were centered corresponding to the still water level in the basin. With the cocks closed to the basin, deflections of the oscillographs were compared with the changes in height of the level bottle. The elements were then isolated from the level bottle and opened to the basin ready to record variations of pressure caused by the passing waves. A comparison of calibrations before and after each set of runs gave information on the stability of the pressure circuits.

The wave machine was controlled electronically. Because of imperfect wave absorption at the walls of the basin, appreciable reflections developed before waves of constant height were produced. Reproducibility was within ±10 pct for heights and ±3 pct for periods.

The wave height probes were of the two-wire type developed by WIEGEL [1947]. These were connected to their Universal Analyser through linearizing circuits. One probe was placed 10.6 ft toward the wave machine from the cylinder axis and 26 inches toward the camera side. The other probe was placed 9.7 ft abeam of the cylinder axis on the camera side.

Convenient synchronizing marks were made on the records by simultaneously dipping wires attached to each bridge circuit into a can of water.

The 16-mm motion camera was arranged to show the electric timer clock, the cylinder water line, the two height probes, and the hands of the operator as he made the timing marks .

Results--The results of this experiment cover the following ranges of variables for non-breaking waves: wave lengths from 5.7 to 14.0 ft; wave height/wave length ratios of from 0.0037 to 0.030; water depth constant at 1.40 ft; periods from 1.1 to 2.2 sec; and products of wave number and cylinder radius from 0.67 to 1.65.

Within the experimental accuracy and ranges of variables of this preliminary test, the diffraction theory was shown to predict the heights of the waves at the cylinder wall and the pressures of the water near the water surface in both magnitude and phase.

The pressure variation near the surface corresponded to the variation of the water surface. The decrease of pressure with depth was shown to be more rapid than the MacCamy - Fuchs postulate indicated. Specific results can be seen in the accompanying figures and tables.

Discussion--It must be emphasized that this experimental work was intended to be indicative rather than precise. The accuracy and reproducibility of the data were low. Apparent anomalies that might have occurred could not be checked because the test basin was dismantled before the data could be analysed. The underlying purpose was to gain sufficient experience to conduct a more precise investigation later under more favorable conditions.

Four sets of data were reduced to forms suitable for comparison with the theory and are presented in Table 1 and in Figures 1 and 2. Because of imperfect absorption of the waves at the walls of the pool, there were appreciable reflections before steady height waves could be produced. Consequently a wave for analysis was chosen which occurred before the reflections were noticeable in the pictures and after the oscillograph records indicated only slow variation of wave heights.

In the table the principal variable is angular position measured from the seaward side, or front, of the cylinder. A comparison is made, in the columns marked 'surface,' between the ratios of the water level at the cylinder wall to the incident wave height as predicted by the diffraction theory, as measured from the motion pictures, and as extrapolated from pressure readings below the surface. These values might be useful in determining the freeboard required for an island subjected to similar waves. The agreement of the three sets of values is of interest. The theory is supported by experiment. The water pressure near the surface is equivalent to the surface height, indicating a lack of impact or stagnation pressure for these non-breaking waves. There may be a deficit of pressure around 150° caused by some of the energy of the wave at these points being in the form of

Table 1--Tabulated results

Wave parameters[a]	Angle from front	Z/d = 0[b] (surface)			Z/d = 0.050		Z/d = 0.286		Z/d = 0.523		Z/d = 0.762	
		Theory[c]	Experiment		Theory	Experiment[e]	Theory	Experiment	Theory	Experiment	Theory	Experiment
			Motion pictures	Pressure[d]								
ka = 1.65 L = 5.74 ft L/d = 4.10 L/D = 1.37 H = 0.170 ft H/L = 0.0296 T = 1.10 sec	0	1.817	1.69	1.66	1.70	1.46	1.25	0.72	0.956	0.35	0.797	0.20
		-0.17	0.37	. . .	. . .	-0.63	. . .	-0.17	. . .	0.40	. . .	-0.28
	30	1.775	1.50	1.33	1.66	1.18	1.21	0.63	0.931	0.28	0.780	0.20
		-0.19	0.20	. . .	. . .	-0.51	. . .	-0.17	. . .	0.97	. . .	-0.17
	60	1.550	1.28	1.31	1.45	1.10	1.06	0.49	0.815	0.24	0.680	0.16
		0.22	-0.11	. . .	. . .	-0.45	. . .	-0.23	. . .	0.68	. . .	-0.11
	90	1.365	1.14	1.14	1.28	0.99	0.937	0.45	0.719	0.19	0.600	0.12
		-0.10	-0.60	. . .	. . .	-0.80	. . .	-0.68	. . .	0.34	. . .	-0.11
	120	0.872	0.95	0.76	0.818	0.63	0.597	0.28	0.459	0.11	0.383	0.09
		0.04	-0.85	. . .	. . .	-0.34	. . .	-0.11	. . .	0.91	. . .	-0.11
	150	0.530	0.62	0.35	0.496	0.32	0.363	0.16	0.279	0.08	0.232	0.04
		0.94	. . .	. . .	. . .	0.63	. . .	0.97	. . .	1.65	. . .	1.20
	180	0.782	0.60	0.66	0.733	0.56	0.537	0.23	0.411	0.11	0.343	0.07
		1.56	. . .	. . .	. . .	0.86	. . .	1.54	. . .	2.80	. . .	1.87
ka = 1.23 L = 7.69 ft L/d = 5.49 L/D = 1.82 H = 0.145 ft H/L = 0.0189 T = 1.35 sec	0	1.75	1.70	1.80	1.68	1.57	1.37	0.80	1.17	0.46	1.05	0.35
		-0.20	-0.19	. . .	. . .	-0.19	. . .	-0.15	. . .	-0.09	. . .	-0.11
	30	1.72	1.71	1.94	1.64	1.67	1.34	0.80	1.14	0.38	1.03	0.34
		-0.21	-0.11	. . .	. . .	-0.51	. . .	-0.43	. . .	-0.17	. . .	-0.37
	60	1.60	1.50	1.56	1.53	1.34	1.26	0.67	1.07	0.32	0.96	0.30
		-0.25	-0.18	. . .	. . .	-0.42	. . .	-0.30	. . .	-0.14	. . .	-0.22
	90	1.28	1.25	1.36	1.22	1.09	1.00	0.43	0.85	0.26	0.76	0.25
		-0.20	-0.27	. . .	. . .	-0.45	. . .	-0.42	. . .	-0.26	. . .	-0.34
	120	0.760	0.96	0.99	0.95	0.81	0.60	0.35	0.51	0.17	0.45	0.18
		0.05	-0.22	. . .	. . .	-0.05	. . .	-0.03	. . .	0.19	. . .	0.09
	150	0.660	. . .	0.71	0.63	0.62	0.52	0.35	0.44	0.23	0.39	0.21
		0.84	. . .	. . .	. . .	0.65	. . .	0.71	. . .	0.79	. . .	0.71
	180	0.850	. . .	0.76	0.73	0.68	0.66	0.40	0.57	0.20	0.51	0.19
		1.18	. . .	. . .	. . .	1.11	. . .	1.11	. . .	1.13	. . .	1.19
ka = 0.675 L = 14.0 ft L/d = 10.0 L/D = 4.67 H = 0.052 ft H/L = 0.00372 T = 2.21 sec	0	1.57	1.57	1.63	1.54	1.50	1.45	0.89	1.36	0.68	1.31	0.52
		-0.26	-0.30	. . .	. . .	-0.08	. . .	-0.02	. . .	0.31	. . .	0.03
	30	1.52	1.51	1.63	1.49	1.51	1.40	0.94	1.32	0.73	1.27	0.45
		-0.29	-0.30	. . .	. . .	-0.53	. . .	-0.03	. . .	0.19	. . .	-0.06
	60	1.34	1.39	1.30	1.32	1.15	1.23	0.76	1.16	0.67	1.12	0.39
		-0.29	-0.32	. . .	. . .	-0.34	. . .	-0.12	. . .	0.11	. . .	-0.40
	90	1.05	1.12	1.07	1.03	0.97	0.97	0.60	0.91	0.62	0.88	0.28
		-0.22	-0.32	. . .	. . .	-0.28	. . .	0.00	. . .	0.17	. . .	0.11
	120	0.782	0.84	0.84	0.77	0.77	0.72	0.50	0.68	0.21	0.66	0.23
		0.15	-0.27	. . .	. . .	0.22	. . .	0.33	. . .	0.78	. . .	0.64
	150	0.880	0.89	0.94	0.86	0.84	0.81	0.50	0.76	0.29	0.74	0.33
		0.63	0.23	. . .	. . .	0.55	. . .	0.66	. . .	0.94	. . .	1.00
	180	0.955	0.96	1.10	0.94	0.95	0.88	0.49	0.83	0.20	0.80	0.31
		0.68	0.44	. . .	. . .	0.42	. . .	0.98	. . .	1.15	. . .	1.15

Note: Numbers in upper rows are for pressures and heights, lower rows are for phases. Pressures and heights are expressed in ratios to the heights of the field waves. Phases are in radians and refer to the field wave crests with negative numbers leading.

[a] Symbols: a is cylinder radius, D is cylinder diameter, d is still water depth, H is wave height, k is wave number ($kL = 2\pi$), L is wave length, T is period.

[b] Depth below still water level divided by water depth is Z/d.

[c] Theoretical values are calculated from Wiener's tables and MacCamy-Fuchs theory.

[d] Pressures extrapolated to Z = 0 from submerged pressure tap readings.

[e] Phases from oscillograph records.

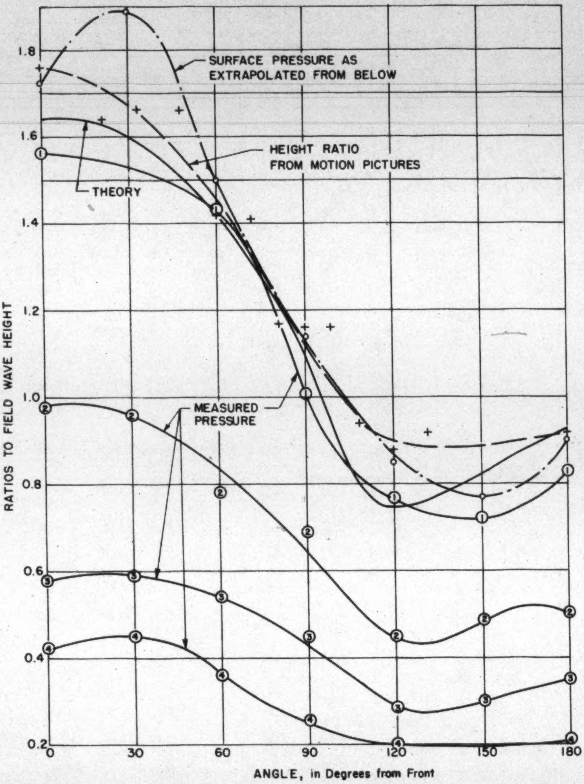

Fig. 1--Ratios of maximum pressures and heights to field wave heights as a function of angular and vertical position; pressure readings 1, 2, 3, and 4 at depth to water depth ratios of 0.050, 0.286, 0.523, and 0.762 respectively; theory from Weiner (data correspond to Fig. 3)

kinetic energy where the velocity of the water is greatest. The one high value in the third section of Table 1 may be due to the long wave length.

The comparison of theoretical and experimental pressure ratios for subsurface levels is shown in the remaining eight columns of the table. The argument, Z/d, is the ratio of the distance below the the surface to the water depth. The decrease of pressure with increasing depth is seen to be more rapid than was predicted by the MacCamy - Fuchs hypothesis that has been used previously by MORISON and Others [1950] for forces on piling. Since these are pressure variations, it may be that the square of the velocity variation should be used. The experimental values, however, indicate an even more rapid decrease.

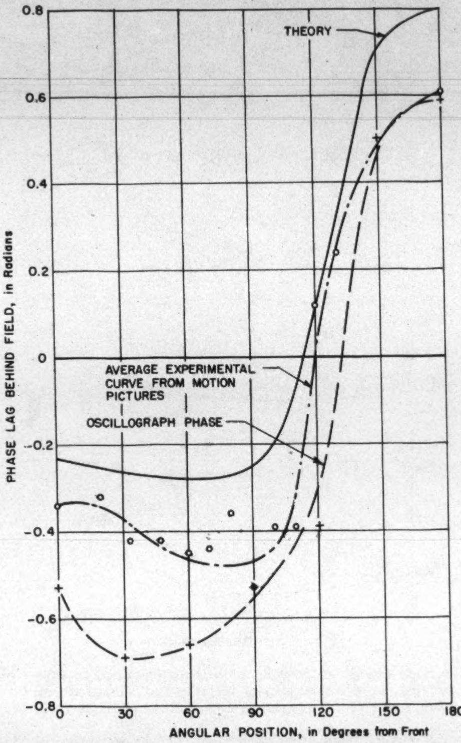

Fig. 2--Variation of phase, relative to field waves, with angular position around the cylinder; theory from Weiner (data correspond to Fig. 3)

In the lower row for each position, phase with respect to the wave field is shown. At the surface the phase from the diffraction theory and the experimental phase from the motion pictures are compared. Because shadows made picture reading difficult in some cases, and precise phase measurements required accurate timing, scatter was to be expected. The phases measured from the 5-mm/sec oscillograph tapes by means of a millimeter scale and magnifying glass show as close agreement with theoretical value for the surface as could be expected.

In Figures 1 and 2 one set of data is presented to show the results graphically. The surface elevations as read from the motion pictures for this set are shown in Figure 3. Some scatter is noticeable but the shapes of the curves are sufficiently well defined to show phases and heights.

The variation of wave action with angular position is clearly shown. The waves were highest at the front of the cylinder and decreased toward the back to become equal to the field waves at about 120°. A minimum height was reached around 150° followed by an increase to a little less than the field height at 180°.

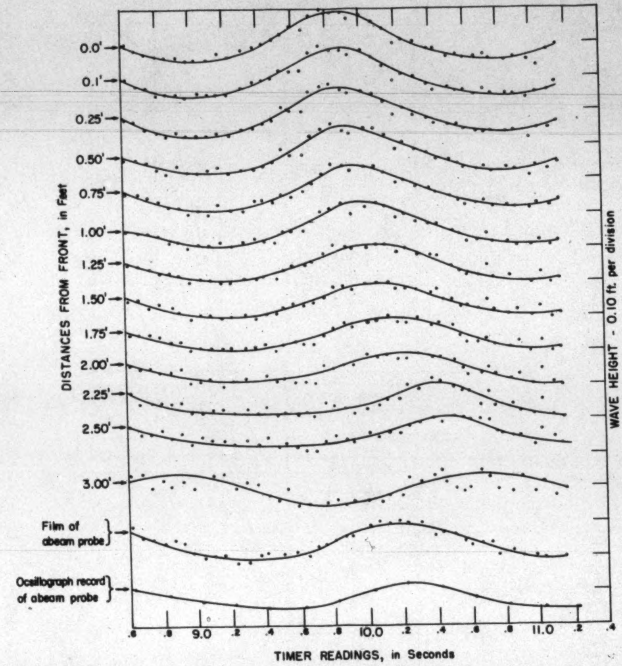

Fig. 3--Water surface heights at the cylinder wall for one wave as a function of time and distance from front as read from motion pictures and compared with the oscillograph record (ka = 0.809, L = 11.7 ft, L/d = 8.32, L/D = 3.89, H = 0.081 ft, H/L = 0.0069, T = 1.90 sec)

The phase also follows the theoretical prediction. The waves at the cylinder led the field waves by a nearly constant amount up to about 90°. Beyond 90° a rapid retardation was noted with the waves being in step near 120°. Thereafter the waves at the wall were retarded increasingly up to about 160°. Between 160° and 180° the lag increased slowly to a maximum at the back.

The velocities around the cylinder were not measured in this experiment but would be of interest in future studies and might give insight into some of the peculiarities of this type of wave action.

The results of this investigation are in essential agreement with those of HELLSTRÖM and RUNDGREN [1954] for similar waves.

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STEADY THREE-DIMENSIONAL FLOW TO A WELL IN A TWO-LAYERED AQUIFER

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Abstract--In Part I, a solution is obtained for the potential distribution induced by a well screened in uniform sand and pumping from it at a constant rate. This sand is overlain by another sand of different permeability, over whose upper surface the potential is uniform. The potential remains constant also at the common outer boundary of both sands, which is concentric with the well. A sample calculation is made for an assumed set of the parameters of the system. For all practical values of the parameters in leaky aquifers, the validity of earlier assumptions made to reduce three-dimensional problems to two dimensions is verified.

In Part II, the solution obtained is for the case where the steadily discharging well is screened in the upper of the two sands. In this case, the two layers of sand are bounded above and beneath by impervious strata. The other boundary conditions are the same as those stipulated for the problem described in Part I. From the general solution, the potential distribution is obtained for the flow towards a well partially penetrating a single sand.

PART I--WELL TAPPING LEAKY AQUIFER SEMI-CONFINED ABOVE

Introduction--By assuming the leakage through an aquiclude into a confined aquifer to be vertically downward and totally refracted at their interface, and by considering the leaking water to be uniformly distributed throughout the thickness of the aquifer, JACOB [1946] reduced the three-dimensional radial flow toward a well in a leaky aquifer to a two-dimensional one and obtained the following steady-state solution

$$s = (Q/2\pi T)\,[K_0\,(r/B) - K_0\,(r_e/B)\,I_0\,(r/B)/I_0\,(r_e/B)] \quad \ldots\ldots\ldots\ldots (1)$$

where Q is the discharge of the well, T is the transmissibility of the confined aquifer, I_0 and K_0 are respectively the modified zero-order Bessel functions of the first and second kinds, r_e is the radius of the outer boundary, and $B = \sqrt{Kbb'/K'}$, b and b' being the thicknesses of the bottom and top beds, and K and K' their respective hydraulic conductivities, with $K >> K'$.

Eq. (1) is valid only when the above restrictions are met. The present paper develops the general steady-state solution with these restrictions removed.

In Figure 1 are shown the two horizontal beds of different hydraulic conductivities, K' in the upper bed, and K in the lower. The two beds are saturated with water from the impervious base

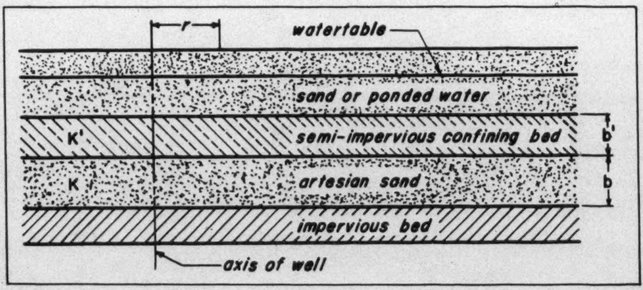
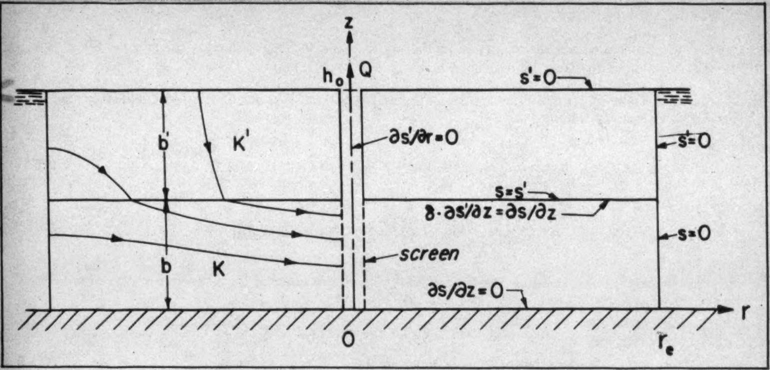


Fig. 1--Diagramatic representation of a stratified artesian aquifer of the lower bed to the top of the upper bed, which is covered with ponded water or overlain by a highly transmissive sand with a water table. The upper bed is of thickness b′ and the lower is of thickness b. A well, idealized as a sink, is screened in the lower bed and is located at the center of the circular aquifer, around whose outer boundary the potential is maintained at a constant uniform value. If the well is pumped at a constant rate, the induced flow within the region is radially symmetrical and three dimensional in nature. The drawdowns in the upper and lower beds are designated by s' and s respectively.



z
h_o
Q
$s'=0$
$\partial s'/\partial r=0$
$s'=0$
b'
K'
$s=s'$
$\delta\cdot\partial s'/\partial z=\partial s/\partial z$
$s=0$
screen
b
K
$\partial s/\partial z=0$
r
0
r_e

Fig. 2--Diagramatic representation of steady three-dimensional flow to a well in a two-layered aquifer

Development of the solution--The system of flow being radially symmetrical, the natural coordinates will be those of the cylindrical system, with the origin as shown in Figure 2. The Laplace equation for ground water flow is then written as

$$\nabla^2 s = (\partial^2 s/\partial r^2) + (1/r)\,(\partial s/\partial r) + (\partial^2 s/\partial z^2) = 0$$

where $s = s\,(r, z)$ is the drawdown at a point whose coordinates are r and z. Analytically the problem may be further stated to be that of finding simultaneous solutions of the following system of equations

$$\left.\begin{aligned} \nabla^2 s' &= 0 && \text{in the upper bed} \\ s'\,(r, h_o) &= 0 && \text{where } h_o = b + b' \\ \partial s'\,(0, z)/\partial r &= 0 \\ s'\,(r_e, z) &= 0 \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (2)$$

$$\left.\begin{aligned} \nabla^2 s &= 0 && \text{in the lower bed} \\ \partial s\,(r, 0)/\partial z &= 0 \\ \lim_{r\to 0}\left\{2\pi K r\int_0^b [\partial s\,(r, z)/\partial r]\,\partial z\right\} &= -\,Q \\ s\,(r_e, z) &= 0 \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (3)$$

$$s'\,(r, b) = s\,(r, b) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

$$\delta[\partial s'\,(r, b)/\partial z] = \partial s\,(r, b)/\partial z \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

where $\delta = (K'/K)$.

It is easily shown that Conditions (2) and (3) are satisfied by the following solutions

$$s' = (Q/2\pi T) \sum_{n=1}^{\infty} A_n J_0 (\alpha_n r) \sinh [\alpha_n (h_0 - z)] \quad \ldots\ldots (6)$$

$$s = (Q/2\pi T) [- \ln (r/r_e) + \sum_{n=1}^{\infty} B_n J_0 (\alpha_n r) \cosh (\alpha_n z)] \quad \ldots\ldots (7)$$

where $T = Kb$ and where the α_n are such that $J_0 (\alpha_n r_e) = 0$; that is, the $(\alpha_n r_e)$ are zeroes of the Bessel function of the first kind of zero order.

Setting $z = b$ in (6) and (7), it is clear that if Conditions (4) and (5) are to be satisfied, the A_n and B_n must satisfy the equations

$$\sum_{n=1}^{\infty} J_0 (\alpha_n r) [A_n \sinh (\alpha_n b') - B_n \cosh (\alpha_n b)] = - \ln (r/r_e) \quad \ldots\ldots (8)$$

$$\sum_{n=1}^{\infty} J_0 (\alpha_n r) [\delta A_n \cosh (\alpha_n b') + B_n \sinh (\alpha_n b)] = 0 \quad \ldots\ldots (9)$$

Eq. (8) and (9) are Fourier-Bessel series. The coefficients of these series are determined by the usual method in the interval (0 to r_e). These are

$$\delta A_n \cosh (\alpha_n b') + B_n \sinh (\alpha_n b) = 0 \quad \ldots\ldots (10)$$

$$A_n \sinh (\alpha_n b') - B_n \cosh (\alpha_n b) = 2/[\alpha_n r_e J_1 (\alpha_n r_e)]^2 \quad \ldots\ldots (11)$$

where J_1 is the Bessel function of the first kind of first order.

Solving (10) and (11) for A_n and B_n, and inserting them in (6) and (7), then making the substitution $x_n = \alpha_n r_e$, one obtains

$$s'/(Q/2\pi T) = 4 \sum_{n=1}^{\infty} \frac{\sinh (x_n b/r_e) \sinh [x_n (h_0 - z)/r_e] J_0 (x_n r/r_e)}{[x_n J_1 (x_n)]^2 \left\{(1 + \delta) \cosh [x_n (b + b')/r_e] - (1 - \delta) \cosh [x_n (b - b')/r_e]\right\}} \quad \ldots\ldots (12)$$

$$s/(Q/2\pi T) = - \ln (r/r_e) - 4 \sum_{n=1}^{\infty} \frac{\delta \cosh (x_n b'/r_e) \cosh (x_n z/r_e) J_0 (x_n r/r_e)}{[x_n J_1 (x_n)]^2 \left\{(1 + \delta) \cosh [x_n (b + b')/r_e] - (1 - \delta) \cosh [x_n (b - b')/r_e]\right\}} \quad \ldots\ldots (13)$$

These equations describe the drawdown in the system. They are rapidly convergent and lend themselves to relatively easy calculation.

It is to be observed that if $\delta = 0$, leakage does not take place. Then, as should be expected, s becomes $[- (Q/2\pi T) \ln (r/r_e)]$.

Comparison with approximate solution--In practical flow-systems, δ is often quite small and the thicknesses of the beds are small compared to their radial dimensions. In such cases where δ is small and $h_0 << r_e$, (12) and (13) may be approximated if it is remembered that $\sinh (x) = x$ for small values of x. Thus

$$s'/(Q/4\pi T) = [4b (h_0 - z)/\delta r_e^2] \sum_{n=1}^{\infty} R_n \quad \ldots\ldots (14)$$

$$s/(Q/4\pi T) = -2 \ln (r/r_e) - 4 \sum_{n=1}^{\infty} (R_n/x_n^2) \quad \ldots\ldots\ldots\ldots\ldots \quad (15)$$

where $R_n = [J_0 (x_n r/r_e)]/[(x_n B/r_e)^2 + 1]\ J_1^2 (x_n)$ and where, as defined before, $B = \sqrt{bb'/\delta}$.

That the leakage into the artesian sand is proportional to the drawdown is evident from the following analysis. First, (14) can be put in the form

$$s'/(h_o - z) = (4b/\delta r_e^2)\ (Q/4\pi T)\ \Sigma\ R_n$$

Then

$$\partial[s'/(h_o - z)]/\partial z = [1/(h_o - z)]\ (\partial s'/\partial z) - s'/(h_o - z)^2 = 0$$

or

$$(\partial s'/\partial z) = -s'/(h_o - z) \quad \ldots\ldots\ldots\ldots\ldots \quad (16)$$

Using (16) with the relation

$$V_z = -\ K'\ (\partial s'/\partial z)$$

one obtains

$$V_z = K's'/(h_o - z) \quad \ldots\ldots\ldots\ldots\ldots \quad (17)$$

At the interface of the two beds, $z = b$ and $s = s'$. Making these substitutions, (17) becomes

$$V_z = K's/b' \quad \ldots\ldots\ldots\ldots\ldots \quad (18)$$

which is the relation used in the approximate theory. In this case, z is taken positively upward.

Eq. (15) clearly indicates that for small δ the flow is almost purely radial and independent of the third dimension, as was assumed by JACOB [1946]. Drawdown values obtained by (15) are in close conformity with those obtained from the approximate theory of (1). Table 1 gives drawdown values computed by the two equations for the same set of parameters used by Jacob.

Table 1--Drawdown values for $T = Kb = 20{,}000\ ft^2/day$, $r_e = 100{,}000$ ft, and $B = \sqrt{bb'/\delta} = 20{,}000$ ft

Equations	$s/(Q/4\pi T)$ values for r/ft equal to					
	1000	2000	5000	10,000	20,000	50,000
	and r/r_e equal to					
	0.01	0.02	0.05	0.10	0.20	0.50
(1)	6.228	4.854	3.083	1.849	0.842	0.124
(15)	6.237	4.859	3.081	1.849	0.841	0.123

PART II--WELL TAPPING UPPER OF TWO SANDS WITH NO LEAKAGE

Analysis--In Figure 3 are shown two horizontal beds of different hydraulic conductivities (permeabilities), K in the upper bed, and K' in the lower. The upper and lower beds are respectively of thicknesses b and b'. The two beds are saturated with water from the impervious base of the lower bed to the impervious top of the upper bed. At the outer boundary of the circular aquifer the potential is maintained at a constant uniform value. A well is screened in the upper bed and is located at the center of the circular aquifer. If the well is pumped at a constant rate, the induced flow within the region is radially symmetrical and three dimensional in nature. The drawdowns developed in the upper and lower beds are designated by s and s' respectively.

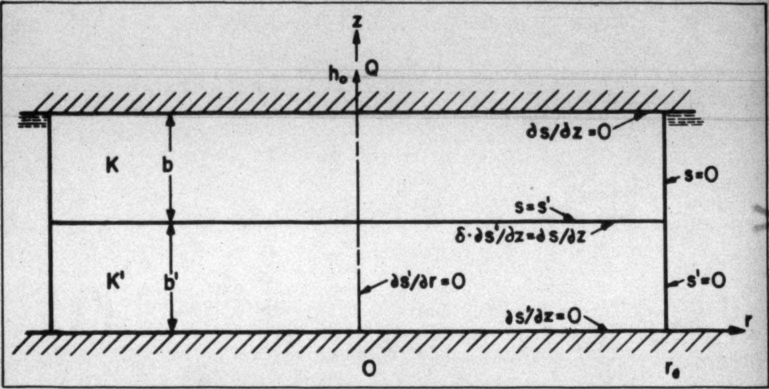


Fig. 3--Diagramatic representation of a well idealized as a sink tapping upper of two sands of different hydraulic conductivities

Case 1--Vanishing well radius--Because the radius r_w of the well is small compared to the other dimensions of practical interest, the well, for analytical purposes, can be considered as a line sink placed at the axis of the well. The required solution will then be the solutions of the following system of equations (see Fig. 3).

$$\left.\begin{array}{l} \nabla^2 s = 0 \\ s\,(r_e, z) = 0 \\ \partial s\,(r, h_o)/\partial z = 0 \qquad \text{where } h_o = b' + b \\ \lim\limits_{r \to 0}\left\{ r \int_{b'}^{h_o} [\partial s\,(r, z)/\partial r]\, dz \right\} = -\,Q/2\pi K \end{array}\right\} \ldots\ldots \quad (19)$$

$$\left.\begin{array}{r} \nabla^2 s' = 0 \\ s'\,(r_e, z) = 0 \\ \partial s'\,(r, 0)/\partial z = 0 \\ \partial s'\,(0, z)/\partial r = 0 \end{array}\right\} \ldots\ldots \quad (20)$$

$$\partial s\,(r, b')/\partial z = \delta \cdot \partial s'\,(r, b')/\partial z \quad \ldots\ldots \quad (21)$$

$$s\,(r, b') = s'\,(r, b') \quad \ldots\ldots \quad (22)$$

where $\delta = K'/K$, and where $\nabla^2 s = 0$ is the Laplace equation for purely radial ground-water flow.

It is easily shown that Conditions (19) and (20) are satisfied by the following solutions

$$s = (Q/2\pi T)\left[-\ln(r/r_e) + \sum_{n=1}^{\infty} A_n J_o(\alpha_n r) \cosh \alpha_n (h_o - z)\right] \quad \ldots\ldots \quad (23)$$

$$s' = (Q/2\pi T) \sum_{n=1}^{\infty} B_n J_o(\alpha_n r) \cosh(\alpha_n z) \quad \ldots\ldots \quad (24)$$

where $T = Kb$ is the transmissibility of the upper bed, and where the α_n are such that $J_o(\alpha_n r_e) = 0$, that is, the $(\alpha_n r_e)$ are zeroes of the Bessel function of the first kind of zero order. Q is the discharge of the well. A_n and B_n can be found in a manner similar to that followed in Part I. The final solution is given by

$$s/(Q/2\pi T) = \ln(r_e/r) - 4\delta \cdot \sum_{n=1}^{\infty} C_n \sinh(x_n b'/r_e) \cosh[x_n(h_o - z)/r_e]\, J_o(x_n r/r_e) \qquad \ldots\ldots\ldots\ldots\ldots\ldots \tag{25}$$

$$s'/(Q/2\pi T) = 4 \sum_{n=1}^{\infty} C_n \sinh(x_n b/r_e) \cosh(x_n z/r_e)\, J_o(x_n r/r_e) \ldots\ldots\ldots\ldots \tag{26}$$

where $x_n = \alpha_n r_e$, and

$$C_n = 1/[x_n J_1(x_n)]^2 \left\{(\delta + 1)\sinh(x_n h_o/r_e) + (\delta - 1)\sinh[x_n(b' - b)/r_e]\right\}$$

Eq. (25) and (26) give the full description of the drawdown distribution in the system. They are rapidly convergent and lend themselves to easy calculation.

It is to be observed that if $K' = 0$, or if $\delta = 0$, flow from the lower bed does not occur. Then, as should be expected, the drawdown becomes simply $s = (Q/2\pi T)\ln(r_e/r)$.

In most practical problems, the thickness of the aquifer h_o is very small compared to its lateral extent, that is, $h_o \ll r_e$, in which case $\sinh(y) = y$ and $\cosh(y) = 1$. If this approximation is made, the solution can be reduced to a simpler form.

Case 2--Finite well radius--An exact solution for this case (Fig. 4) seems to be difficult to obtain. However, since the radius of the well is very small compared to other dimensions, the assumption that there is no flow into the cylindrical core, of radius r_w, below the well, will result in a very insignificant alteration of the flow pattern.

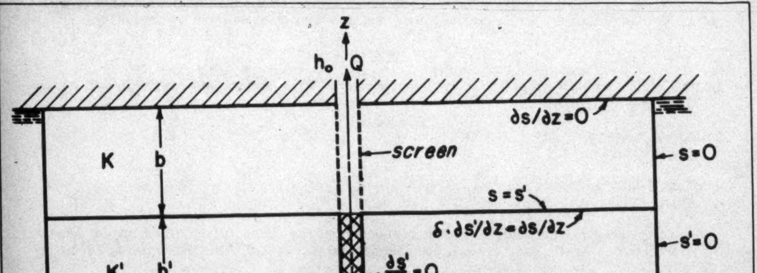


Fig. 4--Diagramatic representation of a well of finite radius tapping upper of two sands of different hydraulic conductivities

By making this assumption the boundary-value problem will be that given by (19) to (22) if the fourth condition in each of (19) and (20) are replaced respectively by

$$r_w \int_{b'}^{h_o} [\partial s(r_w, z)/\partial r]\, dz = -Q/2\pi K$$

and

$$\partial s'(r_w, z)/\partial r = 0$$

In a manner similar to that followed in the preceding development, the solution can finally be put as

$$s/(Q/2\pi T) = \ln (r_e/r) + \delta \cdot \sum_{n=1}^{\infty} F_n \sinh (\beta_n b') \cosh \beta_n (h_o - z)\, U_o(\beta_n r) \quad \ldots\ldots (27)$$

and

$$s'/(Q/2\pi T) = \sum_{n=1}^{\infty} F_n \sinh (\beta_n b) \cosh (\beta_n z)\, U_o(\beta_n r) \quad \ldots\ldots\ldots\ldots (28)$$

where

$$U_o(\beta_n r) = Y_o(\beta_n r_e)\, J_o(\beta_n r) - Y_o(\beta_n r)\, J_o(\beta_n r_e)$$

and where the β_n are such that

$$Y_o(\beta_n r_e)\, J_1(\beta_n r_w) - Y_1(\beta_n r_w)\, J_o(\beta_n r_e) = 0$$

and

$$F_n = [4J_1(\beta_n r_w)\, J_o(\beta_n r_e)]/\beta_n r_w [J_1^2(\beta_n r_w) - J_o^2(\beta_n r_e)] \cdot [(\delta + 1) \sinh (\beta_n h_o) + (\delta - 1) \sinh \beta_n(b' - b)]$$

and where Y_o, Y_1 Bessel function of the second kind of the zero and first orders respectively. The other symbols have the same significance as in Case 1.

Partially penetrating wells--If δ is made equal to unity, the solutions obtained above will reduce to those of a well partially penetrating a single aquifer of uniform permeability.

Reference

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SOME FACTORS AFFECTING RATES OF SEDIMENTATION IN THE COLUMBIA RIVER BASIN

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Abstract--An analysis of stockpond sedimentation survey data and related watershed survey data in the Columbia River Basin revealed that five factors account for 80 pct of the variation in observed sediment in the stockponds studied. These factors include the amount of land subject to accelerated erosion, the original pond storage capacity per square mile of watershed, age of pond, size of watershed, and amount of average annual precipitation. The sedimentation surveys were made during the late summer and fall of 1951 in connection with the development of an agricultural program for the Columbia River Basin by the U. S. Department of Agriculture. The purpose of the surveys was chiefly twofold: (1) to provide information on rates of sedimentation in areas where little or no data were available; and (2) to determine the reduction in sediment which may be achieved by the application of conservation practices. The field data, survey methods, and results of data analysis are given in this report.

Description of area--The stockponds on which the sedimentation data were collected are in the physiographic zones delineated by RAISZ [1941] as the Columbia Basin, Blue Mountain, and Payette-Snake River Plain sections of the Columbia Plateau Physiographic Province.

The Columbia Basin section lies between the Cascade Mountains on the west and the northern Rocky Mountains on the east. Its topography varies from nearly flat to steeply rolling to mountainous, with elevations ranging from about 1000 ft along the gorges of the Columbia and lower Snake Rivers to about 4000 ft around the margins of the province. The basin is dissected by tributary river valleys and, in the northern part, by deep straight-walled coulees of the ancient Columbia River. Continental sediments cover most of the basin, being either wind-deposited or old lake beds. Extensive deposits of glacial material are also found. Lava is exposed in the old glacial outwash channels and in some of the higher ridges. The deeper, more fertile soils are found chiefly in the eastern part of the area. Soils in the central and western part are generally shallow to intermediate, and fine to coarse in texture. The great wheat-fallow and annual-cropping zones of the Columbia River Basin occupy the deeper soils of the Columbia Basin section.

The Blue Mountain section, which extends from southeastern Washington for about 200 mi south and west to central Oregon, consists of an uplifted and subsequently dissected lava plateau surmounted by peaks, of which the highest consist of ancient crystalline rocks. The old and gently sloping plateau surface, where preserved, is smoothly undulating. Canyons are cut from 1000 to 1500 ft below the ridges and expose stratified basalt flows. Elevations reach a maximum of about 9000 ft, but the average range in crest elevations is between 5000 and 6000 ft. Soils are shallow to intermediate and support open grassland at lower elevations and timber at higher elevations.

The Payette-Snake River Plain section extends in an arc through southern Idaho into southeastern Oregon. On the east and in the central part, the lava-covered plains are only slightly dissected, except for the channel of the Snake River and its major tributaries. Toward the west, old lake beds and lava are more highly dissected. Elevations range from about 2000 ft on the west to about 5000 ft on the east. Soils are generally thin and medium to fine textured, except that on the irrigated flood plains of the Snake River and its major tributaries they are deep and vary from coarse to fine in texture.

Climate--The climate in this region east of the Cascade Mountains is arid to semiarid. Compared with the area west of the mountains, this area is characterized by a considerable range in temperature, a low humidity, and a large amount of sunshine. The climate is continental but is modified by the ocean to the west. Most of the precipitation that occurs during the winter is caused by cyclonic storms that develop in the north Pacific area and swing south. A greater proportion of the annual precipitation falls during the summer in the eastern Snake River Plains and at higher mountain elevations than in the west and in lowland areas. Average annual precipitation varies from about six inches in Benton and Franklin Counties, Washington, to more than 60 inches on the crest of the Wallowa Mountain portion of the Blue Mountain section in Wallowa County, Oregon.

The maximum average precipitation is about 43 inches in the area where stockponds were surveyed. Much of the precipitation is in the form of snow, accumulating in the mountains until spring. Sudden thaws, frequently associated with warm 'Chinook' winds, cause high runoff and severe erosion.

Land use--The predominant land uses in the lowland and foothill parts of the area include annual cropping, crop-fallow, and range. The higher mountains and some of the foothill slopes are in forest. The annual-cropping zone is generally in an area of from 16 to 30 inches rainfall. Cropping practices may include grain every year, grain alternating with beans or other cash crops, or in rotation with grass and legumes. In the crop-fallow zone, where precipitation usually varies from eight to 16 inches, wheat is generally seeded in the fall and harvested the following summer. The land is then left in fallow until the following year. Late spring, summer, and early fall forage is available from the perennial or annual range. In the Snake River Plain, the non-irrigable areas are used predominantly for range and in the Blue Mountain section for range and forest.

Table 1--Location, size, and age of stockponds

Record number (1)	Name of stockpond (2)	Geographical location: Section (3)	Geographical location: Township (4)	Geographical location: Range (5)	State and County (6)	Original storage capacity (7)	Original surface (8)	Date storage began[a] (9)	Date of sedimentation survey (10)
			°	°		ac ft	area-acres		
					Washington				1951
1	High Valley Ranch no. 1	9	15N	18E	Yakima County	8.61	1.47	1939	October 16
2	High Valley Ranch no. 2	21	15N	18E	Kittitas County	0.58	0.22	1940	October 17
3	High Valley Ranch no. 3	23	16N	18E	Kittitas County	1.53	0.28	1940	October 17
4	Henry Clerk	1	17N	20E	Kittitas County	2.38	0.75	1946	October 18
5	Coffin Sheep Co.	18	16N	17E	Yakima County	2.63	0.70	1939	October 16
6	Mrs. Weiss no. 1	11	8N	44E	Asotin County	1.45	0.45	1945	September 27
7	Mrs. Weiss no. 2	18	8N	44E	Asotin County	2.54	0.46	1945	September 28
8	Lester Reeves no. 1	11	8N	44E	Asotin County	1.45	0.34	1941	September 27
9	Lester Reeves no. 2	2	8N	44E	Asotin County	1.21	0.25	1945[b]	September 28
10	Dan Holt	4	21N	45E	Spokane County	2.20	0.44	1944	October 22[c]
					Idaho				
11	Roy T. Wood	19	33N	1W	Lewis County	4.22	0.86	1946	September 20
12	Ed Knowlton	15	36N	1W	Nez Perce County	2.54	0.51	1946	September 20
13	Weldon Wassem	5	35N	2W	Nez Perce County	4.58	0.74	1945	September 19
14	Henry Kortemeier	5	38N	2W	Latah County	2.71	0.66	1943	September 21
15	George Hoidal	4	39N	3W	Latah County	2.49	0.51	1941	September 25
16	Johanna Nelson	30	39N	2W	Latah County	5.16	1.40	1943	September 24
17	Ed Galloway	31	39N	2W	Latah County	1.29	0.30	1944	September 24
18	A. K. Tweedy	9	35N	1E	Lewis County	0.80	0.16	1931[d]	September 26
19	Andy Anderson	6	12N	1W	Washington County	104.20	15.85	1905	August 31
20	Milton Branch	34	13N	2W	Washington County	44.49	8.26	1940	September 3
21	W. B. Winninger	7	13N	3W	Washington County	17.58	3.21	1943	August 30
22	Miller Smeed	8	8N	3W	Payette County	2.90	0.75	1945	September 10
23	Twin Puddles	36	2N	1E	Ada County	7.82	3.15	1941	September 27
24	Lambkin	9	2S	6E	Elmore County	4.54	1.54	1941	September 11
25	Mud Springs	33	1S	6E	Elmore County	12.18	3.34	1939	September 11
26	Rattlesnake Butte	22	4S	15E	Gooding County	25.56	9.13	1943	September 13
					Oregon				
27	Luther Claypool	29	16S	23E	Crook County	3.79	1.49	1946	October 8
28	Paul Jaegar no. 1	8	4S	21E	Gilliam County	1.82	0.57	1943	October 2
29	Paul Jaegar no. 2	12	4S	22E	Gilliam County	3.19	0.62	1946	October 2
30	Paul Jaegar no. 3	7	4S	22E	Gilliam County	3.04	0.62	1944	October 3
31	J. M. Wilson	29	4S	17E	Sherman County	1.08	0.51	1946	October 4
32	Willard Barnet	22	2S	16E	Sherman County	2.91	1.04	1941	October 4
33	Arthur Schmidt	13	7S	15E	Wasco County	2.00	0.66	1940	October 9[b]
34	Rock Creek Improvement Co.	14	4S	11E	Wasco County	250.00	13.00	1938	October 9[b]
35	Vernon Christ	2	1S	12E	Wasco County	1.61	0.92	1941	October 10
36	Milt J. Martin	34	1N	12E	Wasco County	2.72	1.19	1944	October 10
37	Hunt Livestock Co.	13	6S	14E	Wasco County	2.25	0.51	1942	October 10
38	J. J. Colton	8	8S	41E	Baker County	1.08	0.58	1939	October 25

[a] Storage usually began in fall of year after construction during summer.

[b] Built in 1941; thoroughly cleaned in 1945.

[c] Reconnaissance type survey.

[d] Built about 50 years ago; cleaned in 1931.

Investigation of stockpond sedimentation surveys--A two-man field party made the surveys of sedimentation in the stockponds covered in this report between August 30 and October 25, 1951. Several objectives were considered in selecting the ponds to be surveyed. These included an intention to obtain data on sediment accumulation from as many geographic locations as possible and from various types of watershed and land uses. It was also planned that the ponds should be at least five years old so as to obtain rates of sedimentation as nearly average as possible. Table 1 gives the location, size, and age of stockponds surveyed. Figure 1 shows the general location of the ponds with reference to the boundaries of physiographic provinces and boundary of the Columbia River Basin.

The spillway contour and range lines were established by plane table and telescopic alidade. Water and sediment depth measurements were obtained by use of the spud in submerged pond areas and by a screw-type auger where the sediment was exposed. Measurements were taken along range lines and were located by plane-table intersection. Water and sediment volumes were computed by the modified prismoidal formula explained on pages 158-161 of USDA Technical Bulletin 524, Silting of Reservoirs.

High evaporation, water consumption by livestock, and months without significant precipitation lowered the water level in many ponds until they were almost dry at the time of survey. This is a seasonal occurrence and, because the sediment from pond to pond was similar in texture, that is, silt and clay with a minor amount of fine sand, it was assumed that the density of deposits was uniform. No samples were obtained for determination of density.

The original capacity of the stockponds varied from about 0.6 to about 250 ac ft and the surface area from about 0.2 to 16 acres. All of the dams are earth fills, usually with rock riprap on the upstream face.

Table 2 gives the data obtained from the sedimentation surveys of the 38 stockponds surveyed. Included are original and present water-storage capacity, age, sediment volume, and loss in capacity. The data obtained show total losses in water-storage capacity ranging from about one to 43 pct and average annual losses from less than 0.1 pct to more than seven per cent. The average annual rate of sediment production for the period of record ranges from about 18 to more than 8200 cu yd/sq mi of drainage.

Investigation of watershed surveys--Watershed information collected by soils men, agronomists, and range specialists included soil depth and texture, slope, range type and condition, cropland use, and type of conservation practices applied, if any. The watershed boundaries were drawn on aerial photographs. For the larger watersheds, mapping units were delineated in the field and planimetered later in the office. Areas of the smaller watersheds were usually single mapping units.

Table 3 summarizes this information. The data are self-explanatory, except for columns (13) and (14), explained below. In addition to the data on Table 3, the survey personnel learned the recent history of cropland use from the farmers and also made estimates of range conditions. In the multiple correlation analysis, described below, estimates of range condition, which were probably too general in character for this type of analysis, did not prove to be significantly related to rates of sediment accumulation, so they are not shown here.

Analysis of data--Multiple correlation analyses were made in order to determine the effect of watershed characteristics and other major factors on the variation in stockpond sedimentation. In various phases of the analyses, rate of sediment accumulation in cubic yards per square mile per year was treated as the dependent variable. Storage capacity per square mile of watershed, age of pond, and watershed attributes other than the rate of sediment accumulation were treated as independent variables. It was anticipated that the results of the analyses would show the effect of the independent variables upon sediment accumulation. In addition, the method of multiple correlation allows for an evaluation of the significance of the variables and a measure of the probable error in the estimate of the individual effects and the total effect. The approach used has been outlined by SNEDECOR [1946]. It was used by GOTTSCHALK [1947] and by GOTTSCHALK and BRUNE [1950] for data on stockponds in South Dakota and small reservoirs in Iowa, Nebraska, and Minnesota, and by ANDERSON [1949] in California.

The first correlation analysis of the relation of sediment accumulation to associated factors included the per cent of land with shallow or medium and deep soils and the average slope in per cent. These factors did not test statistically significant with the data available. The non-significance probably is partly due to the uniformity of the soil and slope characteristics of the watersheds, and the difficulty of measuring and correctly expressing as a quantity the slight differences that do exist.

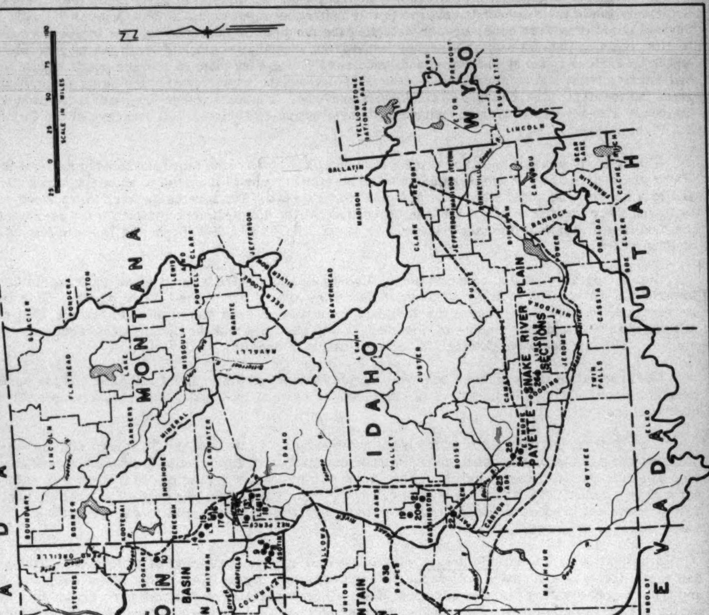
CANADA
WASHINGTON
MONTANA
IDAHO
OREGON
WYO
UTAH
NEVADA
CALIFORNIA
PACIFIC OCEAN
COLUMBIA BASIN SECTION
BLUE MOUNTAIN SECTION
SNAKE RIVER PLAIN SECTIONS
PAYETTE
SCALE IN MILES
25 0 25 50 75 100

Fig. 1--Location of stockpond surveys, March, 1953, Columbia River Basin

Table 2--Results of stockpond sedimentation surveys

Record number	Original capacity	Original capacity per sq mi of drainage area	Sediment volume	Present capacity	Present capacity per sq mi of drainage area	Age at survey	Sediment accumulation		Average annual per sq mi	Loss in capacity	
							Average annual	Average annual per sq mi		Annual	Total
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	ac ft	ac ft	ac ft	ac ft	ac ft	years	ac ft	ac ft	cu yd	pct	pct
1	8.61	2.09	0.98	7.63	1.86	11	0.090	0.022	35	1.04	11.38
2	0.58	3.15	0.07	0.51	2.77	11	0.007	0.038	61	1.10	12.07
3	1.53	4.88	0.11	1.42	4.54	11	0.010	0.033	53	0.65	7.19
4	2.38	0.37	0.36	2.02	0.31	5	0.072	0.011	18	3.03	15.13
5	2.63	5.44	0.16	2.47	5.11	12	0.013	0.027	44	0.51	6.08
6	1.45	11.15	0.22	1.23	9.46	6	0.037	0.280	452	2.53	15.17
7	2.54	11.50	0.40	2.14	9.73	6	0.067	0.304	484	2.63	15.75
8	1.45	14.20	0.27	1.18	11.57	10	0.027	0.264	419	1.86	18.62
9	1.21	9.68	0.52	0.69	5.52	6	0.087	0.696	1129	7.16	42.98
10	2.20	19.80	0.09	2.11	19.01	7	0.013	0.117	189	0.58	4.09
11	4.22	281.40	0.35	3.87	258.00	5	0.070	5.109	8241	1.66	8.29
12	2.54	115.45	0.42	2.12	96.36	5	0.084	3.818	6162	3.31	16.54
13	4.58	286.25	0.18	4.40	275.00	6	0.030	1.875	3032	0.66	3.93
14	2.71	123.20	0.19	2.52	145.45	8	0.024	1.091	1774	0.88	7.01
15	2.49	56.60	0.08	2.41	54.77	10	0.008	0.182	290	0.32	3.21
16	5.16	397.00	0.19	4.97	382.31	5	0.038	2.923	4710	0.74	3.68
17	1.29	99.20	0.06	1.23	94.62	7	0.009	0.692	1129	0.66	4.65
18	0.80	57.10	0.18	0.62	44.29	20	0.009	0.643	1032	1.12	22.50
19	104.20	170.00	3.53	100.67	163.96	46	0.077	0.125	202	0.07	3.39
20	44.49	102.04	1.25	43.24	99.17	11	0.114	0.261	421	0.26	2.81
21	17.58	29.30	0.88	16.70	27.83	7	0.126	0.210	339	0.72	5.01
22	2.90	13.24	0.19	2.71	12.32	6	0.032	0.145	234	1.09	6.55
23	7.82	4.86	0.30	7.52	4.67	10	0.030	0.019	31	0.38	3.84
24	4.54	23.40	0.05	4.49	23.14	10	0.005	0.026	42	0.11	1.10
25	12.18	11.28	0.37	11.81	10.94	12	0.031	0.029	47	0.25	3.04
26	25.56	5.30	1.67	23.89	4.96	8	0.210	0.043	69	0.82	6.53
27	3.79	3.48	0.20	3.59	3.29	5	0.040	0.037	60	1.06	5.28
28	1.82	2.91	0.42	1.40	2.24	8	0.050	0.080	129	2.88	23.08
29	3.19	6.80	0.68	2.51	5.35	5	0.136	0.290	484	4.26	21.32
30	3.04	12.16	0.23	2.81	11.24	7	0.033	0.132	213	1.08	7.57
31	1.08	0.72	0.11	0.97	0.65	5	0.022	0.015	24	2.04	10.19
32	2.91	13.80	0.50	2.41	11.42	10	0.050	0.237	382	2.28	22.83
33	2.00	17.24	0.03	1.97	16.98	11	0.003	0.026	42	0.14	1.50
34	250.00±	44.48	3.20	246.80	43.91	13	0.250	0.044	71	0.10	1.28
35	1.61	18.00	0.22	1.39	15.62	10	0.022	0.250	40	1.37	13.66
36	2.72	38.86	0.14	2.58	36.86	7	0.020	0.286	461	0.74	5.15
37	2.25	45.00	0.10	2.15	43.00	9	0.011	0.22	355	0.49	4.44
38	1.08	2.25	0.24	0.84	1.75	12	0.020	0.042	68	1.85	22.22

Several tests were made of a variable that was expected to denote the significance of land use and treatment. Together with some of the variables given above, the per cent and amount of land in cultivation during the erosion season and the amount of land in poor-condition range were tested in a multiple correlation analysis but did not prove to be significant. An agronomy specialist, without reference to the sedimentation survey data, then estimated what per cent of the land in each cultivated watershed would be subject to accelerated erosion annually, based on the history of land use and crop rotations during the winter runoff season. In the range watersheds, the percentages for the amount of watershed in annual grasses and sagebrush were added together. Percentages for both cultivated and range land were then assumed to represent the amount of land in each watershed subject to erosion. This assumption implies that perennial grass cover serves as adequate protection for the soil, whereas annual grasses and sagebrush do not. Many instances are known in the Columbia Basin where the density of perennial grass cover is not sufficient to afford protection against erosion. However, the theory that annual grass indicates an abused range and that sagebrush is without sufficient ground litter, so far as these watersheds are concerned, was tested.

It is generally known that an acre of eroding range land does not usually contribute the same amount of soil as an acre of cultivated land, other conditions being equal. This is due in part to the greater soil disturbances created by tillage operations than by the trampling of range land by stock. Certain prior experimental data indicated that soil loss from an acre of range land amounts to one-tenth of that from an acre of cultivated land with other conditions equal. In order to obtain

Table 3--Summary of stockpond watershed data

Record number	Drainage area	Average annual rainfall	Soil type		Average slope	Land use						Watershed area subject to accelerated erosion	
			Depth	Texture		Cropland		Rangeland			Forest		
						Grain-fallow	Annual	Sagebrush	Annual grass	Perennial grass			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
	acre	inch			pct	pct	pct	pct	pct	pct	pct	pct	ac/sq mi
1	2634	10	Shallow	Light to medium	15	...	...	20	65	15	...	8	51
2	118	12	Intermediate	Light to medium	35	...	...	3	5	92	...	1	6
3	200	11	Intermediate	Light to medium	35	...	...	22	16	62	...	4	26
4	4143	8	Shallow	Light to medium	25	...	...	20	15	65	...	4	26
5	309	18	Intermediate	Light to medium	20	...	...	15	20	65	...	4	26
6	83	24	Intermediate	Heavy	8	86	...	...	...	14	...	43	275
7	140	30	Intermediate	Heavy	8	79	...	...	...	21	...	40	256
8	65	25	Shallow	Heavy	8	100	...	...	...	...	...	50	320
9	80	20	Shallow	Heavy	10	100	...	...	...	...	...	50	320
10	71	20	Intermediate	Heavy	15-30	15	...	...	...	...	85	12	77
11	9	26	Intermediate	Medium	6	100	...	...	...	...	...	66	422
12	14	26	Intermediate	Medium	22	...	100	...	...	...	...	50	320
13	10	23	Intermediate	Medium	14	...	100	...	...	...	...	50	320
14	14	24	Intermediate	Medium	9	...	100	...	...	...	...	12	480
15	28	27	Intermediate	Medium	22	...	30	...	...	...	70	23	147
16	9	26	Intermediate	Medium	6	...	100	...	...	...	...	75	480
17	9	26	Intermediate	Medium	10	...	100	...	...	...	...	66	422
18	9	26	Shallow	Medium	10	...	100	...	...	...	...	75	480
19	393	17	Intermediate	Medium	10	...	...	67	15	18	...	8	51
20	279	16	Deep	Medium	8	33[a]	...	29	25	13	...	5	32
21	348	15	Shallow	Medium	3	6	82	12	...	...	...	12	77
22	140	11	Deep	Medium	15	...	...	...	95	5	...	10	64
23	1032	12	Shallow	Medium	2	6[b]	...	45	15	...	...	6	38
24	124	14	Intermediate	Medium	3	...	...	100	...	...	...	10	64
25	690	15	Shallow to intermediate	Medium	13	...	...	21	59	20	...	8	51
26	3084	9	Shallow to deep	Medium to heavy	5	...	...	15	85	...	...	10	64
27	700	15	Intermediate	Heavy	5	...	...	100	...	...	...	7	45
28	400	13	Intermediate	Medium	5	93	...	...	...	7	...	47	301
29	300	12	Intermediate	Medium	10	97	...	...	...	3	...	49	314
30	160	13	Intermediate	Medium	7	88	...	...	...	12	...	44	282
31	960	9	Deep	Medium	4	73	...	...	...	27	...	37	237
32	135	11	Deep	Medium	5	78	...	...	...	22	...	39	250
33	74	9	Shallow	Medium	5	...	...	76	...	24	...	8	51
34	3600	21	Intermediate	Medium	6	...	...	...	...	...	100	0	0
35	57	18	Intermediate	Medium	4	100	...	...	...	...	...	50	320
36	45	20	Intermediate	Medium	6	5	...	...	51	...	44	7	45
37	32	10	Shallow	Medium	5	...	...	50	...	50	...	5	32
38	310	10	Shallow	Medium	5	...	...	...	75	25	...	8	51

[a] Alfalfa.

[b] 34 pct alfalfa improved pasture.

a numerical expression for range land subject to accelerated erosion comparable to that for cultivated land, each percentage figure for range land should therefore be divided by ten. This was done and the percentage figures expected to provide a uniform expression of erosion condition in each watershed are shown in column (13) in Table 3. The percentages were then converted to acres per square mile of watershed, column (14), and the logs of these numbers then became a variable.

A scatter-diagram analysis of sediment accumulation versus each of the independent variables showed a departure from linearity in most instances. Similar plottings on logarithmic ruled paper gave evidence that characteristics of the exponential growth curve applied to the data. The numerical values of all variables were, therefore, transformed to logarithms for use in the multiple regression analyses.

The following equation was developed to account for sediment production in relation to size of drainage area, age of pond, original storage capacity per square mile of watershed, average annual precipitation and amount of land subject to erosion per square mile.

$$\log S_5 = 0.9426 + 0.4694 \log OC - 0.7374 \log Age - 0.2059 \log DA$$
$$+ 0.8705 \log AP + 0.2082 \log LSE \ldots\ldots\ldots\ldots \quad (1)$$

where S is the computed annual sediment accumulation in cubic yards per square mile of drainage area by (1), OC is original capacity of the pond in tenths of acre feet per square mile of watershed, Age refers to the period between date of construction and date of survey, DA is drainage area in acres, AP is long-term average annual precipitation in the watershed area in inches, and LSE is the amount of land subject to erosion per square mile of watershed.

The standard error of estimate from the above equation is 0.342 log units and the correlation coefficient 0.893, which expresses an 80 pct account of the variation in annual sediment accumulation. The standard errors of the various partial regression coefficients were: for log OC, ±0.1349; for log Age, ±0.3154; for log DA, ±0.1273; for log AP, ±0.4686; and for log LSE, ±0.1288.

The t test for significance of the individual regression coefficients showed that the variable OC was significant at the one per cent level, Age at the five per cent level, and the remainder at about the ten per cent level. By analysis of variance, however, it was determined that all of the variables were highly significant. The results of this analysis are given in Table 4.

Table 4--Analysis of variance

Source of variation	Degrees of freedom	Sum of squares	Mean square
Total (five variables)	5	14.7534	2.9507[a]
OC	1	5.8239	5.8239[a]
Age	1	1.0704	1.0704[a]
DA	1	3.2174	3.2174[a]
AP	1	2.7186	2.7186[a]
LSE	1	1.9231	1.9231[a]
Error	32	3.7459	0.1171
Total		18.4993	

[a]significant to the one per cent level.

It can be seen from the above table that OC accounts for more than 39 pct of the explained variation, Age about 7 pct, DA almost 22 pct, AP about 18 pct, and LSE about 13 pct. The reason for a much higher significance of most variables by analysis of variance rather than by the t test for significance is believed due to the interrelated qualities of the variables excluding Age. For example, precipitation, in addition to directly influencing the amount of erosion and thus sediment production, also indirectly influences the capacity of the ponds per square mile of watershed. More storage space is generally built into the ponds in a humid area than in the more arid sections. The amount of annual precipitation also influences the amount of land subject to erosion, with more land in the humid zone annually cropped and thus subject to erosion, if not protected, than in the drier area.

Application of analysis--The multiple correlation analysis shows that five factors or variables account for 80 pct of the total variation in sediment accumulation in the stockponds surveyed. In order to indicate graphically the relative significance of the five transformed variables in contributing to the rates of sedimentation, a range in values was substituted in the equation for each variable. The results provided data on the rate of sedimentation that would be expected if the particular variable were functioning independently, although the discussion above shows that most of the variables were interrelated rather than independent. In order that all data could be plotted on the same graph, the results of these calculations were placed on a uniform basis by reducing each side of the equation (range in the variable and rate of sedimentation) to its percentage in relation to the average for the variable. Plotting these data (Fig. 2) permitted an appraisal of each variable on sedimentation. The averages of each variable are given in Table 5.

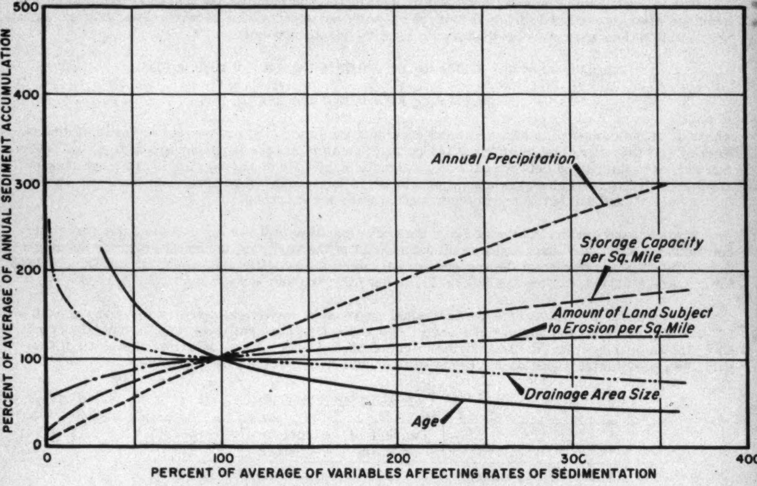

Fig. 2--Effect of five transformed variables on sedimentation

Table 5--Averages of variables used in multiple correlations

Independent variables	Original storage capacity per square mile	54.3	ac ft
	Age	9.6	yr
	Drainage area	548	acres
	Annual precipitation	17.2	inches
	Amount of land subject to erosion per square mile	180	acres
Dependent	Average annual rate of sedimentation in stockponds per square mile of watershed	868	cu yd

The effect of each variable on the annual rate of sedimentation, if it were functioning independently as shown on Figure 2, is discussed below.

Storage capacity per square mile--Eq. (1) and Figure 2 show that as the storage capacity of the pond per unit of watershed increases, the rate of sedimentation increases. The effect is one of increased trap efficiency; that is, more of the sediment entering the reservoir is deposited as spillway losses decrease. This fact has become well established through other investigations, including previous multiple correlation analyses described above. For example, a pond with a storage capacity of about 20 ac ft/sq mi of watershed would trap less than one-third as much sediment as a pond with a storage capacity of about 300 ac ft/sq mi. The curve derived from the changes in this variable describes a gradual arc, except for a more abrupt change in its lower limits. If watershed conditions were homogeneous, it is to be expected that the curve would level off as the storage capacity per square mile of watershed increased to the point where most of the inflowing water and sediment would be held in the ponds.

Age of pond--Average rates of sedimentation have been markedly affected by the age of stockponds, with the rate of sedimentation decreasing with increased age. For example, a pond about four years old shows an annual rate of sediment accumulation almost four times that of one 25 years old. On the other hand, a pond nine years old has an indicated rate of sediment accumulation more than twice that of a pond 25 years old, assuming age as functioning independently of other variables.

The rapidly decreasing rate of sedimentation with an increase in the age of a pond may be due to several causes. In the study by GOTTSCHALK and BRUNE [1950], the effect was attributed to decreasing trap efficiency as sedimentation in the ponds advanced. In the ponds covered in this report, however, the average decline in storage capacity per square mile of watershed has been only about five per cent. According to the curve expressing the effect of storage capacity per square mile of watershed, a difference of five per cent in storage capacity would have a relatively minor effect on the rate of sedimentation. However, some of the losses in storage capacity range up to as much as 22 to 43 pct of the original capacity; so the effect may be greater than that indicated by a comparison of averages.

A more significant reason for the higher rate of sedimentation in younger ponds may be the severe erosion that occurred during two recent years. Heavy soil losses were experienced in the Columbia Basin and adjacent areas in the late winter and early spring of 1949 and 1950. These two spring seasons were preceded by abnormally low January temperatures. The cold and dry weather froze the soils, already moistened by fall rains, to considerable depths. Then a day or so of warm weather thawed the upper few inches. As a result, the surface layer was severely eroded by runoff from precipitation which could not penetrate the underlying frozen soil. Although this cause of erosion is common in the Columbia River Basin, it apparently resulted in much more severe erosion than usual in 1949 and 1950. This could account for the high average sedimentation rate in the younger ponds.

Size of drainage area--The multiple correlation analysis shows that the rate of sedimentation per square mile of watershed decreases as the size of the watershed increased, although the total amount of sediment deposited in the ponds from the larger watersheds is usually greater. The same general relationship between size of drainage area and sediment production has been well established by similar analysis and observations from other parts of the United States. The reason for this relationship is that the larger watersheds offer a greater opportunity for deposition at the base of slopes, along valleys, and in channels above the measuring point. It is also highly probable that complete coverage of a watershed by an intense storm will decrease with an increase in size of drainage area. If the rate of sedimentation were affected only by watershed size, the transformed data show that an area of seven acres would contribute three times as much as an area of 640 acres, and an area of 35 acres about two times as much as an area of 640 acres.

Precipitation--Figure 2 shows that there is almost a straight-line relationship between annual precipitation and rate of sedimentation. Areas having an annual precipitation of eight inches produce less than one-third as much, and areas with 20 inches of precipitation produce about three-fourths as much sediment as areas having 32 inches, other factors being equal. These data show that sedimentation in the stockpond watersheds increases about in proportion to the amount of precipitation. It is known, however, that rates of sedimentation do not increase in proportion to the amount of precipitation in areas without disturbed watershed conditions. For example, the well-forested portions of the Blue Mountains and Cascade Mountains yield a small amount of sediment with an annual precipitation that is double or treble the amounts in the area covered by this report. It should be pointed out that the precipitation data used are long-time averages, whereas the life of the ponds do not include the wide ranges in annual precipitation that may be experienced in the drier zones. Other precipitation variables tested were the average annual precipitation occurring above an intensity of 0.20 inch per day and the frequency of the events above 0.20 inch per day. These variables did not improve the equation. This may be due to the limited precipitation intensity records available.

Amount of land subject to erosion--This variable expressed the effect of cover condition on rates of sedimentation. It was found that sedimentation increased with an increase in the amount of land subject to accelerated erosion. If 75 pct of a watershed had been recently tilled, was bare or was in a low-density crop such as fall seeded wheat during the winter and early spring months, for example, the rate of sediment accumulation would be about two and one-half times greater than from a watershed with five per cent of the land subject to accelerated erosion.

In order to determine the effect of conservation practices on sediment production, the agronomists estimated the amount of land that would be subject to erosion after conservation practices had been installed. The estimates were substituted for the data in column (14) of Table 3 and rates of sedimentation were computed. A comparison of the two sets of data on rates of sedimentation showed that the average reduction for all the ponds studied was about 20 pct and varied from zero in ponds with watersheds already in good condition to 43 pct in ponds whose watersheds are in need of extensive treatment. In view of the interrelated nature of variables used, it is believed that a considerably greater effect of conservation treatment may be found if it were possible to isolate the variable for land subject to erosion. This could probably be done if data were available for a number of ponds in any one physiographic unit.

Limitations of multiple correlation analysis--There are certain limitations in the use of multiple correlation (1). The results may be in considerable error if the significant variables are used for computation of rates of sedimentation in ponds without survey data. This is believed to be due principally to the wide variations in some of the watershed characteristics included in the development of the equation. Figure 3 shows the relation of computed sediment rates to measured rates in the stockponds surveyed. Since the equations are an expression of average effect, some computed sedimentation rates differ rather markedly from measured rates where variables are near the upper and lower limits of the range.

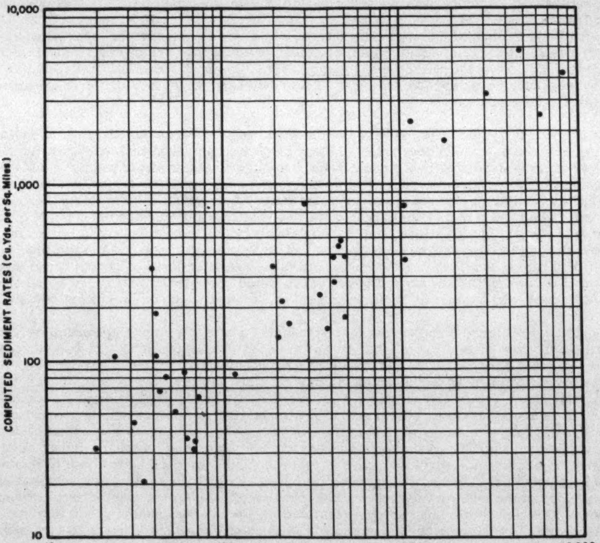

Fig. 3--Relation of measured to calculated rate of sedimentation in stockponds

No area of similar characteristics (for example, the Latah-Nez Percc-Lewis County, Idaho annual cropping zone) is represented by a broad range of watershed sizes, pond storage capacities per square mile of watershed, and ages. The same is true for the group of ponds and their watersheds in the wheat-fallow and range areas. If it were possible to increase the range in data in watersheds with similar characteristics, the effect of the variables acting independently and shown graphically on Figure 2 may be somewhat changed.

Conclusions--The stockpond sedimentation surveys and related watershed investigations provide useful information on rates of sedimentation in portions of the Columbia Basin, where little information was formerly available. The multiple correlation analysis also provides information on the aggregate and partial effects of the major sources of variation in sediment accumulation.

Of value to the conservationist is the fact that cultivated land subject to accelerated erosion was found to be a significant factor, when expressed as the amount of land without adequate protection during the winter erosion season. Range land subject to accelerated erosion was a significant factor, when expressed as the acres per square mile of watershed in annual grasses and sagebrush. The other variables determined to be significant provide a means for judging the effect of original storage capacity per square mile of watershed, age of stockpond, size of drainage area, and average annual precipitation on rates of sedimentation. However, the 38 stockponds are included in a broad area involving heterogeneous climatic, soils, and land-use conditions.

The high standard error does not permit accurate determinations of the rates of sedimentation for specific ponds. Until more data are available within homogeneous areas, the results provide only an aid for estimating rates. Certain areas differ so widely in soil types and slopes from the areas in which ponds are located that severe limitations are put on use of these results even for making estimations. Such areas are the Palouse and Walla Walla Watersheds in the Columbia Basin section. The data are applicable, therefore, only within the ranges of factors measured and should not be used indiscriminately for computing sedimentation beyond these ranges. Probably their most useful function is in providing tools for evaluation of various watershed climatic and land-use characteristics.

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CAPILLARY LOSSES FROM GROUND WATER

Irwin Remson and G. S. Fox

(Publication authorized by the Director, U. S. Geological Survey)

Abstract--A method is presented for estimating the discharge of ground water by evapotranspiration of water rising from the water table by capillarity. 'Potential capillary water loss' is defined as a measure of the ability of the capillary interstices of a soil to raise water from the water table to the ground surface. Published equations describing soil-moisture movement and published graphs relating capillary conductivity and capillary potential are used to derive expressions of the relation between 'potential capillary water loss' and depth to the water table in a given soil. On the basis of these theoretical relationships, graphs are drawn that show how the depth to the water table affects the ability of a particular soil to raise water to the ground surface under given conditions. The application of these methods is discussed in relation to the estimation of ground-water losses by capillary rise, the determination of potential evapotranspiration, and the analysis of soil-tank data. Their essential agreement with empirical profiles of capillary potential obtained in soil tanks demonstrates their usefulness.

Introduction--In the course of the hydrologic investigations of the U. S. Geological Survey at Seabrook, N. J., it became desirable to estimate water losses resulting from capillary rise from water-table aquifers. Such estimates are often based upon local experience or upon pure speculation. However, by applying certain principles of soil-moisture movement, reasonable estimates can be made of the magnitude of this effect.

Theory--The actual capillary water loss from a ground-water body in a given situation will depend upon the evaporating ability of the atmosphere at that time and upon the capillary lifting ability of the soil. In order to study the latter effect, it is necessary to introduce a measure of capillary water loss that is independent of evapotranspiration. Therefore, 'potential capillary water loss' will be defined as the rate at which water would rise to the ground surface from the water table under the influence of capillary forces if the potential rate of evapotranspiration were equal to that rate. Under such conditions, the capillary water would be removed as quickly as it reached the surface, and the moisture content and capillary potential would remain constant throughout all parts of the soil-moisture profile. This theoretical rate represents the maximum capillary loss for a given soil and water-table condition as independent of evapotranspiration. It is a capillary property determined only by the soil and the position of the water table and is completely independent of the ability of the atmosphere to remove moisture from the soil.

Eq. (1), originally given by RICHARDS [1931] as a general equation for upward capillary flow, applies to an isotropic and homogeneous soil when there is only steady-state vertical flow.

$$K\,(\delta^2\psi/\delta z^2) + (\delta K/\delta z)\,(\delta\psi/\delta z) + g\,(\delta K/\delta z) = 0 \quad \ldots\ldots\ldots\ldots\ldots (1)$$

where

K = the capillary conductivity, in sec
ψ = the capillary potential (or tension), in ergs/gram
z = the depth to the water table, in cm
g = the acceleration of gravity, in cm/sec^2

For unsaturated flow, the capillary conductivity K is a function of the moisture content and, consequently, of the capillary potential ψ of the medium. Figure 1 is a modification of Richards' curves relating the capillary conductivity and the capillary potential for a sandy soil A, for the Greenville loam soil B, and for the Preston clay C. The approximately straight-line relationship for the intermediate soil type, the Greenville loam, is described by

$$K = a\psi + b \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where a and b are constants. For a material whose capillary conductivity-capillary potential curve satisfies these conditions, (2) may be substituted into (1) to give a differential equation that has been solved by Richards. He obtained the relationship expressed by (3) for the boundary condition $z = 0$, $\psi = 0$. This boundary requirement merely establishes the datum for z at the water table, where the capillary potential is zero. Then, for any other point in the column of soil

$$z = \frac{1}{g^2a^2C_1} \ln \frac{1 - gaC_1b}{1 - ga^2C_1\psi - gaC_1b} - \frac{\psi}{g} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where C_1 is a constant of integration.

Richards' form of the flow equation for the unsaturated case is

$$q = K\,[(-\,\delta\psi/\delta z) - g] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where q is the capillary water loss, either potential or actual depending upon the individual situation, in cubic centimeters per second per square centimeter of surface. Richards uses the value of K from (2) and the value of $\delta\psi/\delta z$ from the first integration to simplify (4) to

$$q = -\,1/aC_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Eq. (3) and (5) may be combined and simplified to give

$$z = -\,\frac{q}{g^2a} \ln \frac{q + gb}{q + ga\psi + gb} - \frac{\psi}{g} \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Eq. (6) may be used to determine the potential capillary water loss q for any material whose capillary conductivity-capillary potential curve is linear. It is necessary only to substitute into the relationship the height above the water table of any point in the profile z and the capillary potential at that point ψ. The values of a and b can be determined from the conductivity-potential curve.

The Greenville soil, used by Richards in this analysis, shows a nearly linear conductivity-potential relationship in semi-logarithmic plot (Fig. 1). However, for most soils, this relationship will not be approximately linear. For such materials, the different relationship between capillary conductivity and capillary potential must be substituted into (1) in order to derive the applicable formulas.

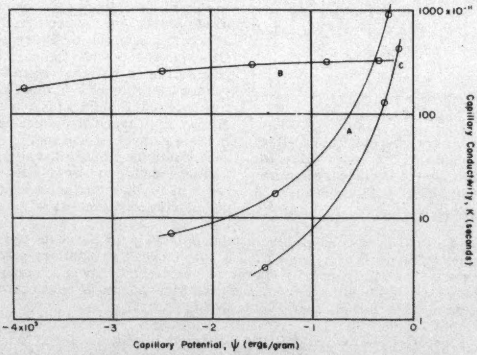

Fig. 1--Relation between capillary conductivity and capillary potential for a sandy soil A, Greenville loam soil B, and Preston clay C (adapted from L. A. Richards)

Applications to ground water--The variation of potential capillary water loss with water-table depth and with surface capillary potential may be studied by applying (6). Assume that the material in question is the Greenville loam so that Richards' values of $a = 5.35 \times 10^{-15}$ and $b = 3.85 \times 10^{-9}$ will apply. The value of g may be taken as 980.6 cm/sec^2. Consider first the case for which the surface soil is at a negative capillary potential of 332,500 ergs/gram. This is equivalent to the potential produced by a negative pressure equivalent to 25 cm of mercury or one-third of an atmosphere. Some workers consider these conditions as representative of field capacity [COLMAN, 1947].

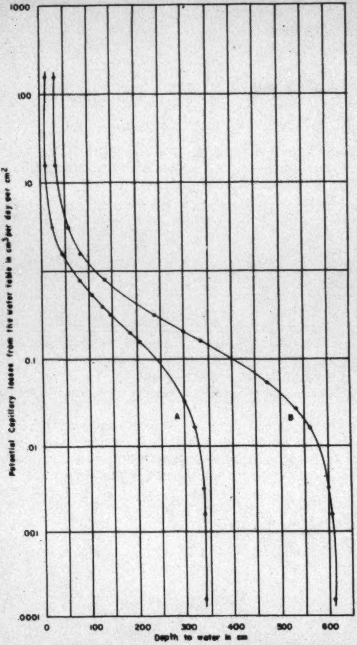

Fig. 2--Relationship between potential capillary water loss and depth to the water table for Greenville loam when the surface is at a negative capillary potential of 0.33 atmosphere A and 0.59 atmosphere B

Curve A in Figure 2 was obtained by substituting the values of g, a, b, and ψ into (6). It shows how the depth to the water table affects the potential capillary water loss for the Greenville loam when the surface material is at a negative capillary potential of one-third of an atmosphere. The effect of the depth to water is striking. For a water-table depth of 12 cm, the potential capillary water loss is 160.5 cm^3 per day for every square centimeter of area. For a water table at a depth of 80 cm, the potential loss is a little less than one cubic centimeter per day per square centimeter. Below a depth of 300 cm, the rate of potential water loss decreases very rapidly with depth. It must be emphasized that these figures represent potential losses and not actual ones. Therefore, they indicate what the Greenville soil is capable of raising to the surface rather than what the actual losses will be.

Figure 1, which was adapted from Richards, shows the relationship between capillary conductivity and capillary potential in the range between $\psi = 0$ and $\psi = -4 \times 10^5$. In addition, experimental data tabulated by Richards shows that for $\psi = -6 \times 10^5$ ergs/gram, K is approximately 72 sec for the Greenville loam [RICHARDS, 1931], and the approximately linear relationship still holds true in this range of values. Therefore, (6) could be used to show how the depth to the water table affects the potential capillary water loss for the Greenville loam when the surface is at a capillary potential of -6×10^5 ergs/gram. Curve B in Figure 2 was derived in this fashion. This negative potential of 0.59 atmosphere applies to conditions drier than for the previous case, but still in the wet range of soil moisture. However, it represents the limit of the available data listed by Richards for the Greenville soil. Furthermore, it is likely that these equations break down under drier conditions as will be discussed below.

The Greenville soil has been used in this discussion largely for purposes of illustration. However, capillary conductivity decreases more rapidly with increasing capillary potential in the other soils whose curves are shown in Figure 1. Therefore, they would show much smaller capillary losses than would the Greenville soil under similar conditions. This is borne out by the study of potential losses from another soil discussed later in this paper.

The available conductivity-potential data for the Greenville loam extends to a potential of -0.59 atmosphere. Because permanent wilting does not occur until a potential of -15 atmospheres is reached, it can be appreciated that Richards' data covers a very small part of the available moisture range. The straight-line relationship exemplified by the equation $K = a\psi + b$ would break down in the drier ranges, and the capillary conductivity would decrease at an accelerating rate. Eventually, the decreasing capillary conductivity would counterbalance the increasing potential gradient. Then, the trend suggested by the two curves in Figure 2 would be reversed and the potential capillary losses would be cut down as the surface material continued to dry.

A drying soil will eventually reach a condition in which the capillary conductivity is reduced to such a low value in the surface layers that little water will reach the surface. MOORE [1939] presents graphs for different soils showing the capillary potentials for which the capillary conductivity becomes essentially zero. He shows that for a soil whose moisture content has been reduced to the permanent wilting percentage, both the actual and the potential capillary losses from the water table will be negligible. Of course, under field conditions, when the water table is close enough to the surface so that potential capillary water loss is in excess of potential evapotranspiration, drying of the soil cannot occur.

Applications to climatology--Potential capillary water loss has been defined so that it is independent of evapotranspiration. Thus, it is analogous to potential evapotranspiration, which has been defined so that it is independent of soil moisture [THORNTHWAITE, 1948]. 'Potential evapotranspiration' is the amount of water that would be transferred to the atmosphere by a land surface completely covered with vegetation provided that an optimum amount of soil water were available to supply the needs of the vegetation. Actual evapotranspiration and actual capillary water loss are, however, interdependent and largely determine and restrict each other.

Our computations have shown that for a water table at a depth of 12 cm in Greenville loam and a negative surface potential of one-third atmosphere, the potential capillary water loss is 160.5 cm^3 per day for every square centimeter of area. However, a potential evapotranspiration loss of even one cubic centimeter per day per square centimeter would be large. Thus, if an experiment were set up in Greenville loam so that the water table were at a depth of 12 cm and the negative surface potential were equal to one-third atmosphere, it is apparent that there would be sufficient water available at the surface for evapotranspiration to occur at the potential rate. Furthermore, whereas the potential capillary water loss would be 160.5 cm^3, the actual loss would be equal to the potential evapotranspiration. The entire soil-moisture profile, therefore, would readjust itself so that the capillary potential gradient and the capillary conductivity would be only large enough to supply an amount of water from the water table equal to the potential evapotranspiration.

It is apparent from the foregoing discussion that the actual capillary water loss and the actual evapotranspiration will be equal to the potential evapotranspiration for the shallow water tables. Thus, potential evapotranspiration may be determined by calculating the actual capillary water loss under such conditions. When there is a linear curve relating capillary potential and capillary conductivity, (6) may be used. For a non-linear curve, the analogous equations may be derived. The shape of the conductivity-potential curve may be developed by means of laboratory measurements [RICHARDS and MOORE, 1953]. The required capillary potential ψ may be readily determined with tensiometers [RICHARDS and NEAL, 1937]. The value of q obtained will be the potential evapotranspiration.

Applications to soil-tank data--There are maintained at Seabrook, New Jersey, instruments designed by C. W. Thornthwaite to measure potential evapotranspiration [MATHER, 1950]. These evapotranspirometers are basically vegetation-covered soil tanks in which stable water tables are maintained and arrangements are made to measure the water losses and gains. Tensiometers are installed at four levels so that it is possible to plot the vertical profile of capillary potential.

At the suggestion of M. H. Halstead of Johns Hopkins University Laboratory of Climatology, an attempt was made to fit the capillary flow equation to the evapotranspirometer data. According to Mather and Halstead [J. R. Mather and M. H. Halstead, Johns Hopkins Univ. Lab. of Climatology, personal communication], previous analysis of the available data had indicated that the capillary conductivity-capillary potential curve for the evapotranspirometer soil was of the form

$$K = a/\psi \quad \ldots\ldots\ldots\ldots \quad (7)$$

This suggested form of the conductivity-tension curve can be substituted into (1) to give

$$a\psi\,(\delta^2\psi/\delta z^2) - a\,(\delta\psi/\delta z)^2 - ag\,(\delta\psi/\delta z) = 0 \quad \ldots\ldots\ldots\ldots \quad (8)$$

The first and second integrals are respectively

$$\delta\psi/\delta z = (\psi - gC_1)/C_1 \quad \ldots\ldots\ldots\ldots \quad (9)$$

and

$$\ln(\psi - gC_1) = (z/C_1) + C_2 \qquad (10)$$

where C_1 and C_2 are the constants of integrations.

The boundary condition $z = 0$, $\psi = 0$ gives $C_2 = \ln(-gC_1)$ and (10) now becomes

$$z = C_1 \ln[(gC_1 - \psi)/gC_1] \qquad (11)$$

When the values of K and $\delta\psi/\delta z$ are substituted into (4) from (7) and (9) respectively, the results may be simplified to

$$C_1 = -(a/q) \qquad (12)$$

This may be combined with (11) to give

$$z = -(a/q) \ln[1 + (\psi q/ga)] \qquad (13a)$$

or

$$\psi = (ga/q) \exp[-(qz/a)] - (ga/q) \qquad (13b)$$

Eq. (13a) and (13b) describe the vertical profile of capillary potential for any soil whose potential-conductivity curve is described by (7). A similar equation has been independently derived in a different fashion for the soil-tank data by J. R. Mather and M. H. Halstead in a personal communication.

The Johns Hopkins University Laboratory of Climatology kindly made available the evapotranspirometer data plotted in Figure 3. The figure shows the capillary potentials, from tensiometer readings, as functions of height above the water table for two days during which the daily measured evapotranspiration was 0.33 cm^3 per square centimeter of surface area.

To test the applicability of (13), the data for the 30-cm level was substituted into this final equation, and a was found equal to -6.5×10^{-5}. Because the soil was originally uniform throughout the evapotranspirometer, it was assumed as an approximation that a was a constant throughout, and (13) was used to determine the theoretical profile. In Figure 3 the theoretical curve has been superposed upon empirical curves so that they may be compared.

The purpose of this discussion is to demonstrate the usefulness of the methods and not to make a detailed analysis of the evapotranspirometer data. Therefore, no attempt will be made to resolve the differences between the curves in Figure 3. However, when considering these differences, it must be recognized that the units for capillary potential are ergs per gram. Because an erg is a very small unit, the ordinate is actually plotted on an expanded scale. For example, the largest discrepancy between tensions of the plotted points is about 65,000 ergs/gram. This amounts to a difference of only 0.06 atmosphere when converted to the more commonly used field units. Thus, the differences between the curves in Figure 3 are not as large as the tension units make them appear to be. The expanded scale is also largely responsible for the differences between the empirical curves.

Part of the discrepancy between the curves in Figure 3 is due to obvious instrumental errors. The capillary potential at the water table, where $z = 0$, is zero. The fact that the empirical curves bend away from the point $z = 0$, $\psi = 0$ indicates errors in the data from the tensiometer at the 15-cm level. Part of the discrepancies might be due also to lack of soil homogeneity throughout the profile, to errors in the measurement of evapotranspiration, or to the possibility that steady-state flow was not present since the tensiometer readings were made only once a day at 08h 00m. The figure used for q is the total evapotranspiration for the day, whereas the profile is an instantaneous one. For greater accuracy, it would be necessary to insert a periodic function for q and take account of the variation of evapotranspiration with time. In addition, more profiles are necessary in order to fix a so that a better fit can be obtained. Finally, it is possible that an equation of the form $K = a/(\psi + b)$ would give a better description of the conductivity-potential curve for the evapotranspirometer soil. Again, more data would be necessary to test this possibility.

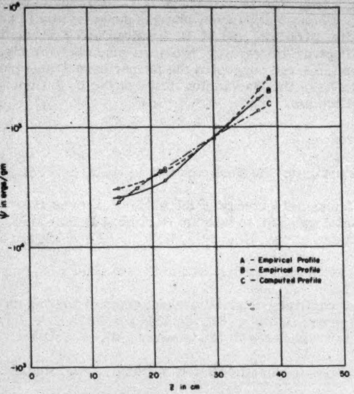

Fig. 3--Computed and empirical relations between height above the water table Z and capillary potential ψ in a Seabrook evapotranspirometer

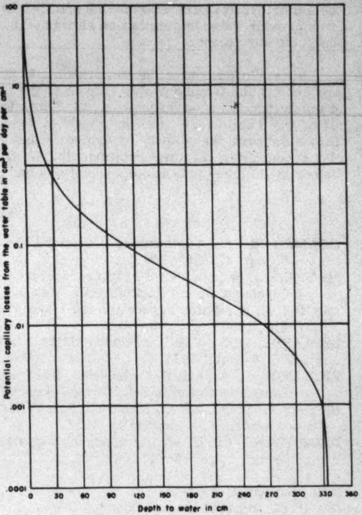

Fig. 4--Variation of potential capillary water loss with water-table depth for evapotranspirometer soil when the surface is at a negative capillary potential of 1/3 atmosphere

In consideration of these facts, it is believed that the theoretical curve in Figure 3 is in sufficiently close agreement with the empirical curves in the range shown to demonstrate the usefulness of the methods.

Figure 4 shows how the depth to the water table affects the potential capillary water loss for the evapotranspirometer soil when the surface is at a negative capillary potential of one-third of an atmosphere. As has been pointed out, a material such as this with its non-linear K - ψ curve has smaller potential capillary water losses than does the Greenville loam for water tables at comparable depths. A comparison of Figures 2 (curve A) and 4 bears this out.

Conclusions--The methods described in this section assume the existence of a field of capillary potential and that the unsaturated flow satisfies the potential equation. This is undoubtedly true at the higher soil-moisture levels. However, many investigators believe that the soil-moisture system becomes discontinuous, and there is no longer a continuous field of capillary potential at moisture levels below field capacity. Then the flow equations would no longer apply. In applying these methods for estimating capillary losses, it must be remembered that the equations are likely to break down in the drier ranges of soil moisture. Under such conditions, they probably would indicate potential capillary water losses in excess of the true values.

The methods presented in this paper are not meant to be tools by which water-table losses from capillary rise can be widely computed. Their application is limited by the scarcity of curves relating capillary conductivity and capillary potential for different materials and by the difficulty of developing such curves [RICHARDS and MOORE, 1953]. The purpose of this paper is rather to point out some of the relations that govern the capillary losses from ground-water bodies. In cases of shallow water tables and the wetter soil-moisture ranges, it may sometimes be expedient to develop the necessary K - ψ curves in the laboratory, and install the tensiometers required by the methods. A good example of their usefulness is the fashion in which they describe approximately the empirical evapotranspirometer profile. In any event, they demonstrate that capillary losses from ground-water bodies can be estimated by suitable application of the relations governing soil-moisture movement.

Acknowledgments--The authors wish to acknowledge the assistance of H. C. Barksdale, Staff Engineer of the Ground-Water Branch of the U. S. Geological Survey, who has supervised all phases of the Seabrook investigations. C. W. Thornthwaite, Director, and M. H. Halstead and J. R. Mather, all of the Laboratory of Climatology of Johns Hopkins University, provided much helpful advice. They also made the evapotranspirometer data available and suggested the proper evapotranspirometer conductivity-potential relationship. W. O. Smith of the Washington office of the U. S. Geological Survey made many invaluable suggestions and criticisms.

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HEATED PRECIPITATION-GAGE INTAKE TUBE

F. C. Allen, R. E. Glover, W. U. Garstka, and H. M. Posz

Abstract--The design and functioning of a heated precipitation-gage intake tube is described. Heat is transported to a specially constructed intake tube through a vapor-phase system using an evaporable liquid having a boiling point of about 40°F at a pressure of one atmosphere. The source of heat is combustion of liquified petroleum gas in a vented space heater which operates intermittently under thermostatic control. The system provides sufficient heat to prevent adherence of snow and ice to a precipitation-gage intake tube, thus preventing the usual capping-over and incapacitation of gages operated under winter conditions. The system was invented as part of the development by the Bureau of Reclamation of an unattended radio-reporting rain and snow gage network now in its third year of service in the Sacramento River Drainage Basin, California.

The problem of the measurement of winter precipitation is common to the world's temperate zones and is critical in the subarctic and arctic zones, both in the northern and southern hemispheres. The frequent inability of existing installations to measure precipitation other than rainfall is well recognized. Although a great deal of effort has been expended on the development of adequate shielding with a high degree of success, nevertheless, the problem of capping-over and incapacitation of gages exposed under winter conditions remains. This is a result of the ability of snow to stick to surfaces, even concave surfaces, when driven at sufficient velocity by the winds

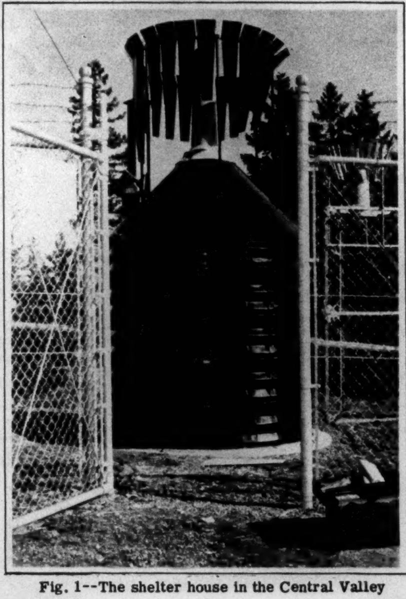

Fig. 1--The shelter house in the Central Valley and when the snow is falling at temperatures such as to result in snowflakes capable of adhering to other surfaces and to each other.

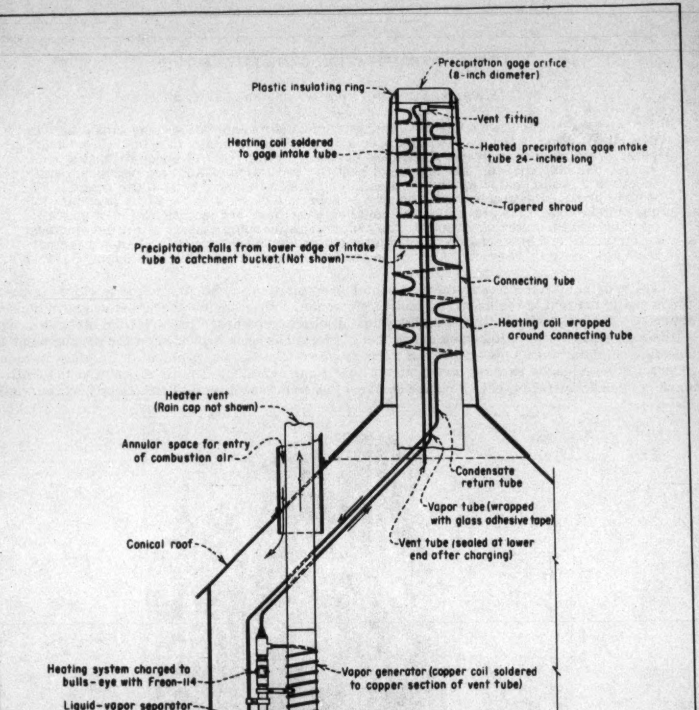
Precipitation gage orifice (8-inch diameter)
Plastic insulating ring
Vent fitting
Heating coil soldered to gage intake tube
Heated precipitation gage intake tube 24-inches long
Tapered shroud
Precipitation falls from lower edge of intake tube to catchment bucket (Not shown)
Connecting tube
Heating coil wrapped around connecting tube
Heater vent (Rain cap not shown)
Annular space for entry of combustion air
Condensate return tube
Vapor tube (wrapped with glass adhesive tape)
Vent tube (sealed at lower end after charging)
Conical roof
Heating system charged to bulls-eye with Freon-114
Vapor generator (copper coil soldered to copper section of vent tube)
Liquid-vapor separator
Wall of shelter
Pressure-actuated liquid stop valve
Fusible plug
Top of space heater (Liquified petroleum gas fuel)
Charging line (Seal end after charging)
Adjustable damper
Floor of shelter

Fig. 2--Diagrammatic arrangement of apparatus for heated precipitation-gage intake tube as assembled for the radio-reporting rain and snow gage network, Bureau of Reclamation, Central Valley Project, California

The incapacitation of gages has been noted especially in connection with the operation of seasonal-storage precipitation gages, although hydrologists and meteorologists have commonly observed partial incapacitation of a gage even by one snow storm. Eight-inch diameter precipitation-gage intakes have been observed supporting a mushroom of snow over three feet in diameter.

The heated intake to the precipitation gage described was developed to supply heat to the intake tube to prevent the adherence of snow, sleet, and ice. In the Central Valley Project installation, a well-insulated shelter house, shown in Figure 1, is kept at a temperature of 45° F by a small space heater which obtains its fuel supply from a tank of liquified petroleum gas. A pilot flame burns continuously in this heater and when the temperature falls below 45° F, a thermostat turns the heater on. The heating period lasts until the shelter is brought up to the temperature required for proper functioning of the electronic and catchment recording equipment.

The apparatus for transferring heat from the warm flue gases discharged from the space heater to the precipitation-gage intake tube consists of two distinct parts, a heat generator and a vapor condenser, which are interconnected by tubular copper vapor and liquid lines as shown in Figure 2. The arrangement is essentially similar to that of a gravity-return vapor heating system.

The heat generator consists of a four-inch diameter section of copper vent pipe about which copper tubing is spirally wrapped. This pipe receives heat from flue gases escaping from the heater. The copper coil is soldered to the copper vent pipe. Adjacent to the copper coil is a tubular accumulator to which the coil is connected both at the bottom and the top. This accumulator serves as a balancing reservoir for supplying liquid to the coil and for separating liquid from the vapor which is expelled at the top of the coil when the apparatus is in operation. A damper at the lower end of the copper flue can be manually adjusted to fix the amount of tempering air admitted to the flue, and thus to fix the effective temperature of the flue gases.

The vapor condenser consists of a tubular copper coil applied to the upper and lower sections of the precipitation-gage intake tube in such a way that the copper tube slopes continuously downward from the top to the bottom. The tubing is soldered to the upper intake tube but is in only superficial contact with the lower tube. An outer shell both supports the intake tubes and forms an insulating air space. Thus, warm vapor entering the coil at the top condenses and gives up heat principally to the intake tube in the upper section and principally to the air in the lower section. Heat conducted along the upper copper intake tube warms the eight-inch diameter collector ring and prevents the accumulation of ice or snow. The warming of the air between the intake tubes and outer shell prevents the adherence of ice or snow to either the inside of the intake tubes or the outside of the outer shell. A small-diameter vent line is provided from the top of the vapor condenser to the space below to provide a means of removing 'non-condensible' gases from the system during the charging operation.

Two low-boiling-point fluids have been used for charging the system, Freon-21 (Dichloromonofluoromethane) and Freon-114 (Dichlorotetrafluormethane). The Freon-114 is preferred principally because of its slightly higher vapor pressure. The absolute vapor pressure of Freon-21 is below one atmosphere at temperatures below 48° F, while the vapor pressure of Freon-114 is below one atmosphere at temperatures below 38° F. Neither fluid produces excessive system pressures, but there will be less tendency for air to enter the system if Freon-114 is used. However, it is imperative that the system be well sealed in order to avoid loss of fluid. The heating system for the intake tube arranged in this way has no moving parts to cause trouble.

A vapor-phase heating system was selected because it is capable of transporting quantities of heat more or less in proportion to the demand. It has the further advantage of permitting the use of small-diameter tubes without introducing problems of viscosity and flow which would have to be met should a liquid-filled system be used. Furthermore, the vapor-phase heat-transport system has the advantage of supplying heat in the largest quantities automatically to the coldest portion of the condenser system. The size of the vapor condenser and of the heat generator was so proportioned that heat would be supplied in sufficient quantities to prevent adherence of snow and ice, but not in sufficient quantities to cause noticeable evaporation. In the Central Valley Project installation, the intake tube is heated whenever the space heater functions.

The pressure-actuated liquid stop valve shown on the diagrammatic arrangement is a refinement in the control system which has not proven to be necessary under the conditions existing in the Central Valley of California. When the space heater is operating with atmospheric temperatures at or below the freezing point, the surface temperature of the intake tube will not exceed the temperatures which occur on a normal summer day. However, the use of this control valve in a heating system designed for extreme or arctic conditions would minimize any tendency toward the development of excessive temperatures and evaporation at the gage intake tube. This valve could be either pressure-actuated or temperature-actuated. If this valve were pressure-actuated, it would be adjusted to close gradually as the system vapor pressure, and consequently the condensing temperature, rises to a predetermined value. This would starve the vapor generator coil and reduce the heating effect. If the valve were temperature-actuated, it would have a temperature-sensing remote bulb connected by a capillary tube to the valve mechanism. This bulb would be inserted into the annular space between the intake tube and the tapered shroud. In either case, the valve would serve to limit the temperature rise of the intake tube during the time the space heater is operating with atmospheric conditions near the freezing point. This automatic control valve would eventually require servicing or replacement, and hence, it should be used only if necessary. As sticky snow usually falls only at temperatures near 32°F, the heating of the intake tube is needed chiefly in the air temperature range of about 20 to 25°F to about 38°F. At temperatures below about 20 to 25°F, the snow is apt to be dry, presenting no adherence and capping problems. In the Central Valley Project installations, it was not considered necessary to incorporate limit controls for the heated precipitation-gage intake tube.

The installation in the Central Valley has been operated for three winters. During that time, no accumulation of snow was observed either on the exterior or interior of the heated precipitation-gage intake tube.

Acknowledgments--The heated precipitation-gage intake tube was invented as part of the development of a radio-reporting rain and snow gage for the Bureau of Reclamation's Central Valley Project, California. The pioneer unit was built and tested by the Bureau's Engineering Laboratories Branch at the Denver Federal Center, Denver, Colorado. An application for a patent covering the heated precipitation-gage intake tube, to be assigned to the United States Government, has been filed with the United States Patent Office.

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TREE GROWTH AND RAINFALL

Waldo S. Glock

Abstract--The relationship of tree growth to that rainfall which furnishes soil moisture for growth has been approached in two ways: by an analysis of growth patterns and by direct correlation. For the latter method, growth-layer sequences were taken from trees which grew in the forest interior.

Tree growth and rainfall are highly complicated processes whose interrelationships may at times seem simple and direct, at other times complex and devious.

Growth factors--The factors which influence growth are both internal and external. Among the internal factors we may include genetic, physiologic, reproductive, growth-promoting or inhibiting, and pathologic. The external factors include the more popular ones, such as rainfall and temperature, and the less popular, such as wind and storms, evaporation and humidity, sunlight or radiation, topography and exposure, fire, soil, and competition.

Soil moisture--Water is a prime necessity in the physiological processes of growth and is obtained from moisture in the soil. This moisture has its direct and major source in rainfall. Therefore, the speed, amount, and direction of infiltration and percolation of moisture are of fundamental importance during the period of active tree growth and determine when and how much soil moisture becomes available to the growing tree.

The work of hydrologists has shown that infiltration and percolation require a matter of hours or a very few days to bring the soil moisture to field capacity through a depth which depends to a great extent upon the amount of water entering the soil. Any water in excess of that necessary for field capacity passes downward out of the zone of percolation into the underground flow of the saturated zone. In addition, percolation maintains a vertical direction under the influence of gravity in so far as differential permeability permits. Reference to the work of VEIHMEYER [1927, 1953], MATHER [1953], and PILLSBURY [1953], to name but a few, emphasizes the relatively rapid rate of percolation as well as the rapid use of available soil moisture by trees during the growing season.

Trees respond to soil moisture directly and almost immediately. MACDOUGAL [1921] reported that an oak responded to irrigation within two hours as recorded by a dendrograph. BYRAM and DOOLITTLE [1950] said that the recovery time of a pine from a lack of water seemed "to be determined only by the time required for the water to reach the roots."

In view of the rapidity of percolation and of growth response to moisture, it is not difficult to visualize conditions in which a soil has its moisture depleted and replenished several times during a single season and in which the trees growing on such a soil cease and begin growth more than once during the season. MACDOUGAL [1923] irrigated a Monterey pine which had ceased growth in mid-summer. After irrigation the tree resumed growth and put down wood of greater thickness than that of earlier in the season. FIELDING and MILLETT [1941] reported that at Canberra, Australia, bursts of growth always followed soaking rains in summer and autumn.

Forest zones--In the Southwest certain forests may be divided into interior and border zones which grade into each other by change of altitude. Available soil moisture at the forest interior is greater and more constant in amount than that at lower altitude where the forest adjoins an arid land. In fact, the fluctuations of such a growth factor as soil moisture may be expected to decrease in wave length and increase in amplitude from forest interior to forest border at the margin of a desert.

The relationship of tree growth to rainfall has been studied by two methods: an analysis of growth patterns and direct correlation.

Rainfall types and growth patterns--Because of the nature of the rainfall regime three rainfall types and their associated growth patterns have been tentatively recognized in the Southwest.

(1) A winter rainy season characterizes the California, or Sierra, type. Plant growth must depend upon soil moisture replenished as a rule during or immediately before the beginning of growth. Hence the growth pattern consists of growth layers which tend to be rather uniform in thickness and single within the annual increment. Exceptions to this unity are known.

(2) Under the West Texas type rainfall comes so intermittently during the growing season that soil-moisture fluctuations are rather intense and follow each other with relative rapidity. Here the growth pattern consists of growth layers which are highly variable in thickness, and multiple and partial within the annual increment.

(3) The Arizona type is intermediate in that it has both winter and summer rainy seasons. The West Texas type apparently extends westward at low elevations and the California type eastward at high elevations. At the line of contact in Arizona a tension zone is set up in the vegetation, the contact rising during dry years and lowering during wet years. Hence the growth pattern shows a growth-layer sequence with alternations of uniformity and variability in thickness, and of unity and multiplicity within the annual increment.

Growth patterns may reveal much information about the rainfall regime by a study of variability in thickness of successive growth layers, relative and absolute thickness variations in circuit and longitudinal uniformity, areal distribution of partial growth layers, and the constitution of the annual increment.

Correlation of tree growth and rainfall--In 1947 a total of nine increment cores was taken from among four species of gymnosperms in the forest interior of north-central New Mexico on and adjacent to Holman Pass. The trees were growing in the upper portion of the ponderosa pine zone (Transition-Canadian), four at 9000-ft, two at 9450-ft, and three at 8000-ft elevation. At 9000 ft, the four trees grew within 150 yards of each other; at 9450 ft, the two trees were 20 yards apart; and at 8000 ft, the three trees were approximately in line and 20 and 80 yards apart. All trees were chosen so that there appeared to be a minimum amount of drainage toward or away from them. In spite of such choice some trees grew on drier sites than others. It was found that the ring records were more homogeneous when the trees were divided into two series, the one from drier and the other from wetter sites, than when divided into three groups on the basis of elevation alone. Ring thicknesses were averaged for dry-site trees, for wet-site trees, and for all trees as a single group whose records extended from 1850 to 1941.

When the individual ring sequences were compared with each other, it became immediately apparent that they showed fewer agreements for the period 1850 to 1897 than for 1898 to 1941. In the earlier period of 48 years there were nine years when the trends were parallel for all sequences whereas in the later period of 44 years there were 15 years of parallel trends, with six agreements concentrated in the ten-year period 1920 to 1929. This division guided all subsequent work.

Analyses were made to determine average thickness of rings and amount of rainfall, and also to determine average variation, average departure, and average departure from mean variation of tree growth and of Santa Fe rainfall of March-July. Although Santa Fe was 40 mi distant, its rainfall record was used because of its length. Average variation depends upon the total difference from year to year whereas average departure depends upon the difference of each year from a mean. Average departure from mean variation was calculated in an attempt to obtain a measure of excess variation over normal. The analyses gave the results indicated in Table 1. With a slight increase in March-July rainfall during the later of the two time periods, the indices for the rainfall as given in the several parts of Table 1 decreased. The several indices for the wet-site trees likewise decreased as did the average thickness of growth layers. The dry-site trees responded in an opposite direction, that is, their indices increased.

At the time the work just discussed was being done, LEOPOLD [1951] was using Santa Fe rainfall in a study of rainfall frequency. He grouped rains into three sizes, 0.01-0.49 inch, 0.50-0.99 inch, and 1.00 inch or more in a day, and contrasted the two periods 1849-1895 and 1896-1939, a division which is almost exactly shown by the ring sequences from the Holman Pass area. It is of immediate interest to note that the number of small rains, 0.01-0.49 inch, was greater in the later period, the average number per year being 81 in contrast with 66 for the earlier period. The average number per year of the large rains, 1.00 inch or more, was 1.7 for the earlier and 1.1 for the later period. Thus Leopold has given us valuable information on rainfall characteristics because studies have shown that small but effective rains coming at close intervals have greater influence on growth than heavier rains more widely spaced.

Table 1--Data on Santa Fe rainfall for March-July and Holman Pass tree growth contrasted for the two periods, 1850-1897 and 1898-1941

Item	1850-1897	1898-1941
Average magnitude		
Rainfall (inches)	6.34	6.74
Dry-site trees (mm)	1.53	1.70
Wet-site trees (mm)	2.26	1.96
Group record (mm)	1.99	1.83
Average variation (per cent)		
Rainfall	42	33
Dry-site trees	26	40
Wet-site trees	38	27
Group record	33	32
Average departure (per cent)		
Rainfall	33	22
Dry-site trees	32	36
Wet-site trees	34	30
Group record	35	31
Average departure from mean variation (per cent)		
Rainfall	25.0	22.0
Dry-site trees	13.2	14.8
Wet-site trees	20.4	11.8
Group record	13.0	10.5

The contrast in growth-layer characteristics between the two periods 1850-1897 and 1898-1941 may be explained in three possible ways: (1) a change in rainfall characteristics or amount, (2) a change in the rainfall period to which growth responded, (3) a change in relationship to optimum and limiting factors, or (4) a combination. In reference to (1), we are fortunate in having the explanation given by Leopold. An increase in the frequency of small rains plus a slight increase in total amount accompanied by a decrease of variation indices in the rainfall was paralleled by a decrease in the indices of growth in the wet-site trees as well as by a decrease in average growth-layer thickness. But the contrary response of the dry-site trees remains unexplained. In reference to (2), Table 1 shows that the average variation of the dry-site trees increased with a decrease of average variation in rainfall. Calculation showed that April-May rainfall actually increased its average variation. Perhaps dry-site trees were more influenced by spring rainfall than were the wet-site trees. Discussion of point (3) is difficult and speculative. It may be that the dry-site trees were sufficiently below the optimum to respond to more frequent replenishment of soil moisture by greater growth and greater variation indices; in contrast, the wet-site trees were so near the optimum that the same soil-moisture changes brought a reduction of growth and a decrease in variation indices. The changes in wet-site trees, however, paralleled the changes in rainfall except for decrease in thickness of growth layers.

Internal agreement among the trees increased from the earlier to the later period and agreement among trees increased with decreasing distance between them, regardless of species. The trees do vary across distances measured in yards.

As a final calculation, tree growth was compared with March-July rainfall, 1909-1941, of Chacon, seven miles distant from the trees. The trend coefficient, which gives a measure of parallel variation combined with amount of that variation [GLOCK, 1950], came out 0.965, and the ratio of opposed trends 0.12. Comparison with stations more remote gave mixed and poorer results. Comparison of single trees with rainfall gave lower results. Where records permitted calculation, the growth layers of the period 1850-1897 showed poorer correlation with rainfall than did those of the period 1898-1941. In other words, correlations were higher when variations of rainfall were less, when the frequency of small rains was greater, and when the amount of rainfall was slightly greater.

The evidence indicates that each tree is individually responsive to the factors immediately surrounding it, that each tree from the forest interior, as here represented, records with some accuracy the rainfall which supplies soil moisture when the tree needs it, that increasing distances bring about increasing differences among trees, and that these trees are rather delicate recorders of changes in rainfall not only by means of changes in internal agreement among the trees but also by means of changes in external agreement with certain rainfall characteristics.

Summary--Two methods of approach to the problem of deriving rainfall from tree growth have been outlined briefly. In the first place, an analysis of growth patterns gives a general picture of the rainfall regime under which the trees grew. In the second place, changes in the moisture supply to trees may be determined by the amount of agreement in directional variation among the growth-layer sequences of the trees themselves and by intercomparisons in average variation, average departure, and especially average departure from mean variation. It seems clear that further detailed analyses of rainfall, so well made by Leopold, and their comparison with tree growth are highly desirable.

Acknowledgments--First I want to express my deep appreciation to Ralph W. Chaney who originally aroused my interest in tree growth and whose friendship and encouragement have been constant since my student days. Because the present report summarizes the work of several years, I am greatly indebted for invaluable assistance at different times on various aspects of the work to a number of organizations, Carnegie Institution of Washington, Society of Sigma Xi, American Philosophical Society, Smithsonian Institution, and most recently the National Science Foundation (Grant NSF-G610). Much gratitude is due Macalester College through its president, Charles J. Turck, for making time and facilities readily available. Finally, the stimulating energy and resourcefulness of N. A. Bowers have been of great value to the progress of the work during the last two seasons.

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A GRAPHICAL SOLUTION OF THE FLOOD-ROUTING EQUATION FOR LINEAR STORAGE-DISCHARGE RELATION

J. E. Nash and J. P. Farrell

Abstract--The problem of routing floods through reservoirs where the storage is a linear function of the outflow is treated, and a simple graphical method of obtaining the discharge from the inflow is presented.

Introduction--The authors in working on the production of synthetic unit hydrographs from basin characteristics frequently found it necessary to route time-area diagrams through various amounts of storage.

The method--In the following equations, I is the inflow in cubic feet per second or similar units; O is the outflow in the same units; S is the storage in the reservoir and is measured in cfs-hours; t is the time from start of routing interval, and T is the duration of inflow in hours. It is assumed that the storage is a linear function of the outflow, that is, $S = KO$. When I, O, and S are function of time t, the equation of continuity is $I = O + ds/dt$, that is

$$I = O + K do/dt \quad \ldots\ldots (1)$$

The general solution of this equation is

$$O = 1/K\, e^{-t/K} \int e^{t/K}\, I\, dt \quad \ldots\ldots (2)$$

This equation can be integrated in cases where I is a simple function of t. For the purposes of this graphical system, it is assumed that the inflow may be taken as a block diagram, that is, the inflow is constant over short intervals.

Constant inflow--Where I is constant throughout the routing interval, the solution of (2) is $O = I + C/K\, e^{-t/K}$, where C is the constant of integration. It may be evaluated as follows: if $O = O_0$ when t is zero, $C/K = O_0 - I$; whence $O = I + (O_0 - I)\, e^{-t/K}$, or

$$I - O = (I - O_0)\, e^{-t/K} \quad \ldots\ldots (3)$$

This means that while the inflow is constant the outflow approaches the inflow logarithmically.

In Figure 1 the discharge is given by (3) between t = zero and t = T. At t = T, the inflow ceases and (3) becomes the well-known equation of the recession curve for discharge from linear storage $O = O_0\, e^{-t/K}$, where t is measured from the cessation of inflow. It is thus clear that I - O between t = zero and t = T and O from t = T to t = ∞ have the same equation and can be represented by different parts of the same curve.

If a curve, Figure 2, is cut out in celluloid or some similar material according to the equation $O = O_0\, e^{-t/K}$, K being measured according to the time scale to which the inflow is plotted, this curve can be used to obtain the outflow as follows: Put the template on the inflow diagram as in Figure 3 with the axis of the curve coinciding with the value of I and slide to the right until the curve passes through the origin. Draw a pencil along the curve up to A, the time at which inflow ceases. It is clear that this represents the outflow between t = zero and t = T. Now turn the template upside down and make the time axis lie along the time axis of the diagram (because I is now zero) and slide to the right until the curve passes through A. Draw in the recession curve of outflow along the template.

Inflow in block form--Very frequently the inflow may be expressed by means of a block diagram and the calculation of the outflow is simply a repetition of the method described above for a constant inflow. Having completed the first block, move the template upwards and to the right until it is in the position shown in Figure 4, that is, the time axis along the inflow value and the curve passing

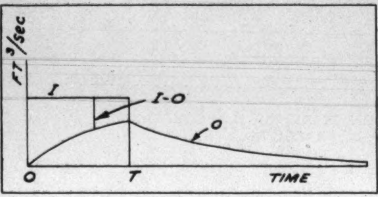

Fig. 1--Inflow constant

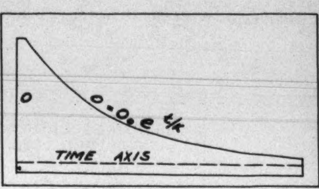

Fig. 2--Example of template for $O = O_0\ e^{-t/K}$

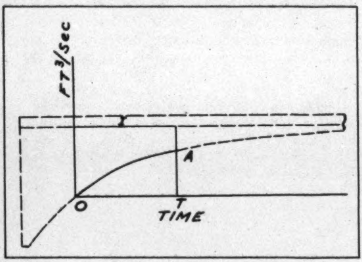

Fig. 3--Use of the template

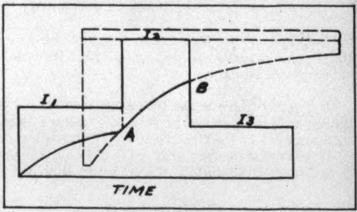

Fig. 4--Next step in the use of the template

through A. Then draw AB along the curve of the template. This procedure may be repeated for any number of inflow blocks until the routing is completed. Any time the inflow is less than the discharge, it will be necessary to turn the template upside down as in drawing the recession curve when I is zero.

The authors have used the method extensively for the purpose stated in the introduction and found it rapid, accurate, and easy of application.

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A PUMPING-TEST METHOD FOR THE DETERMINATION OF SPECIFIC YIELD

Irwin Remson and S. M. Lang

(Publication authorized by the Director, U. S. Geological Survey)

Abstract--The specific yield of a water-table aquifer is one measure of the amount of water within the aquifer that is available for recovery (development). It is expressed as a percentage or decimal fraction of the total volume of material of which the aquifer is composed. The specific yield may be determined during the course of an equilibrium pumping test by comparing the volume of dewatered material in the cone of depression with the total volume of discharge water. An equation is developed theoretically that expresses the volume of dewatered material in terms of test data. A related equation indicates the magnitude of losses at the pumped well. These equations were tested by applying them to test data tabulated in ground-water literature.

Introduction--The determination of the quantity and quality of ground water available for industrial, agricultural, municipal, and domestic supplies is the prime purpose of the ground-water investigations made by the U. S. Geological Survey. Such investigations entail study of the geology and hydrology of an area and study of the geochemistry and hydraulic characteristics of ground-water reservoirs or 'aquifers.'

The Theis non-equilibrium formula and its modifications are generally sufficient for the determination of the hydraulic characteristics of the artesian aquifers involved in ground-water investigations [WENZEL, 1942, pp. 87-89]. However, for water-table aquifers, in which the water is not confined, the available non-equilibrium formulas are not always directly applicable, and more use is made of equilibrium methods. This paper presents a modification of the equilibrium methods whereby it is possible to utilize pumping-test data for determining the hydraulic characteristics of water-table aquifers.

The most important hydraulic characteristics of aquifers that are determined in the course of ground-water investigations are the coefficients of permeability and transmissibility and the coefficient of storage. The coefficient of permeability is a measure of the capacity of a water-bearing material to transmit water; the coefficient of transmissibility is the analogous property of an aquifer as a whole. The unit of measurement commonly used for permeability is the 'Meinzer unit,' or simply the 'meinzer,' which is the rate of flow in gallons per day through a cross-sectional area of one square foot under a hydraulic gradient of one foot per foot at a temperature of 60°F. In field practice, it is customary to use a similar unit of measurement based on the prevailing water temperature, with no adjustment to the standard temperature of 60°F [WENZEL, 1942, p. 7]. The coefficient of transmissibility also is measured at field temperature; it is the flow in gallons per day through a vertical strip of the aquifer one foot wide and extending the height of the aquifer, at unit hydraulic gradient. The coefficient of storage for water-table conditions is essentially the same as the specific yield, which is the quantity of water yielded by gravity drainage from saturated water-bearing material expressed as a percentage or a decimal fraction of the total volume of the material drained. The coefficient of storage is slightly but negligibly higher than the specific yield because it includes the small amounts of water derived from storage by compaction of the beds and expansion of the water in the zone below the water table as the water table declines. The term 'specific yield' is used in this paper because it emphasizes that the paper deals with water-table conditions.

The usual methods for determining the specific yield of shallow aquifers have been either pumping tests, using large numbers of observation wells, or laboratory determinations on formation samples. The laboratory methods can be applied only to very small samples taken at discrete points. The method described herein has the advantage of determining the mean specific yield over a considerable area, as is the case with other pumping-test methods. If the entrance losses at the pumped well are negligible, only one observation well is needed in addition to the pumped well for the determination of permeability and specific yield by this method (permeability being determined by the usual pumping-test methods). However, two observation wells (or a value for permeability obtained from another source) are needed if entrance losses are significant.

Theory--Standard formulas may not be strictly applicable to this situation because it is often impossible to obtain a constant discharge throughout a test in a shallow water-table aquifer and because of the slow drainage of the aquifer material during the test. However, despite the past fluctuations in the yield of the discharging well, if a pumping rate Q is constant for a period of time sufficiently long so that the cone of depression reaches approximate equilibrium form and is declining only very slowly, the general equilibrium formula can be applied. WENZEL [1942, pp. 98-99] describes the condition of approximate equilibrium, "... as pumping continues, a hydraulic gradient that is essentially an equilibrium gradient will be established close to the pumped well, and water will be transmitted to the well through the water-bearing material in approximately the amount that is being pumped. The decline of the water table and the resulting unwatering of material in this area will then be much slower."

The assumptions of equilibrium used in the development of the general equilibrium formula are applied to the derivations presented here. Although the water table continues to decline slowly, the assumption that steady-state conditions have been reached involves only a slight error no greater than that resulting from such a cause as fluctuation in pump discharge. The following paragraph, adapted from WENZEL [1942, p. 77], describes the requisite conditions of the test:

An isotropic and homogeneous water-bearing bed of infinite areal extent is assumed to rest on a relatively impervious formation. The discharging well, equipped with a pump, is fully screened to the bottom of the water-bearing material. It is assumed that water movement from the outer radius of the screen to the pump intake occurs without loss of head or with a head loss that is negligible compared with the drawdown in the well. The water table before pumping, and the underlying impervious bed, are assumed to be horizontal. It is assumed also that there is no recharge to the aquifer during the test and that all the water pumped is removed from storage.

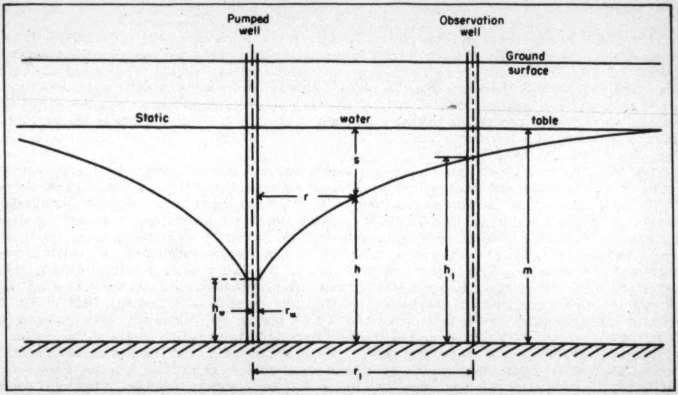

Fig. 1--Diagram showing drawdown of the water table in the vicinity of a pumped well

The following symbols or nomenclature are used in this development (see Fig. 1).

Q = the discharge rate of the pumped well in gallons per day
P = the aquifer's field coefficient of permeability in gallons per day per square foot under a unit hydraulic gradient, and at the prevailing water temperature
I = the hydraulic gradient expressed as a decimal fraction
r = the horizontal distance from the axis of the pumped well to a point on the cone of influence, in ft
h = the height of the same point above the aquifer bottom, in ft
r_w = the outer radius of the pumped well, in ft
r_1 = the horizontal distance from the axis of the pumped well to the axis of the observation well, in ft

h_w = the height of the water level just outside the screen of the pumped well above the aquifer bottom, in ft (It is essentially constant during the near-equilibrium part of any one test.)
h_1 = the height of the water level in the observation well above the aquifer bottom, in ft
m = the height of the static water table above the aquifer bottom, in ft

Ignoring the change in stored volume of water in the area between r_1 and r_w as a function of time, Darcy's law may be used to find the relationship among head, radius, and discharge in the vicinity of the well [WENZEL, 1942, pp. 78-79].

$$Q = P\,(dh/dr)\,2\pi rh \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\int_{r_w}^{r_1} (dr/r) = (2\pi P/Q) \int_{h_w}^{h_1} h\,dh \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$\ln r_1 - \ln r_w = (2\pi P/Q)\,[(h_1^2/2) - (h_w^2/2)] \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$P = [Q \ln (r_1/r_w)]/[\pi\,(h_1^2 - h_w^2)] \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Eq. (4) may be used to determine the permeability of the aquifer when entrance losses are negligible at the pumped well.

In order to determine the volume of material dewatered when the cone of depression reaches essentially an equilibrium or unvarying shape, it is necessary to find an equation which expresses the shape of the cone. For any point on the cone (h, r), (4) can be written as

$$r = r_w \exp\,[(\pi P/Q)\,(h^2 - h_w^2)] \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

The volume of dewatered material in cubic feet V within the cone of influence is expressed by

$$V = \pi \int_{h=h_w}^{h=m} r^2\,dh \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

The value of r from (5) may be substituted in (6) to give

$$V = \pi r_w^2 \int_{h=h_w}^{h=m} \exp\,[(2\pi P/Q)\,(h^2 - h_w^2)]\,dh \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Let $a = 2\pi P/Q$ and $b = -(2\pi P/Q)\,h_w^2$, then

$$V = \pi r_w^2 \int_{h=h_w}^{h=m} \exp\,(ah^2 + b)\,dh \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

which is the volume of dewatered material in the cone of depression.

Eq. (8) may be integrated by first expanding $\exp\,(ah^2 + b)$ into a Maclaurin series of the form

$$f(h) = f(o) + f'(o)\,(h/1!) + f''(o)\,(h^2/2!) + \ldots + f^n(o)\,(h^n/n!) + \ldots$$

This gives

$$\exp\,(ah^2 + b) = e^b \left\{1 + (ah^2/1!) + (a^2h^4/2!) + (a^3h^6/3!) + (a^4h^8/4!) + \ldots + [a^{n-1}h^{2n-2}/(n-1)!] + \ldots\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Cauchy's test-ratio indicates that this series is absolutely convergent for all values of h and a, and therefore may be integrated between the limits h_w and m to give an expression for the volume of dewatered material in the cone of depression.

$$V = \pi r_w^2 e^b \left\{ h + (ah^3/3 \cdot 1!) + (a^2h^5/5 \cdot 2!) + (a^3h^7/7 \cdot 3!) + (a^4h^9/9 \cdot 4!) + \ldots + [a^{n-1}h^{2n-1}/(2n-1)(n-1)!] \right\}_{h_w}^{m} \quad \ldots\ldots (10)$$

where $a = 2\pi P/Q$ and $b = -(2\pi P/Q)\, h_w^2$.

The specific yield, under the conditions stated, is the volume of water pumped during the test divided by the gross volume of dewatered material within the cone of influence.

$$S = Qt/7.48V \quad \ldots\ldots (11)$$

where

S = the specific yield
Q = the average discharge rate of the pumped well, in gallons per day
t = the time, in days, since pumping began
V = the volume of dewatered material, in cu ft, determined from (10)

Application--When the assumptions made in the theoretical development are fulfilled by the test conditions, only a discharging well and one observation well are required to obtain the aquifer permeability and specific yield. However, in many tests there are significant entrance losses at the pumped well, and the formula cannot be used to determine permeability. In many cases reliable figures for permeability can be obtained by other means, such as laboratory tests or pumping tests on other wells. If a reliable figure for permeability is available, the method can be used to determine specific yield and entrance losses. When there are significant entrance losses, the value h_w cannot be observed directly, even by means of an observation well just outside the pumped well because of the likelihood that installation of the pumped well resulted in disturbance of the water-bearing material.

Assuming that a reliable value for P is available from another source, if the drawdown at any point on the cone of depression, in feet, is denoted by s, $h = m - s$ which can be substituted in (5) and the result rearranged to give

$$h_w = \left\{ (m - s)^2 - [Q \ln (r/r_w)/\pi P] \right\}^{0.5} \quad \ldots\ldots (12)$$

The value of P and the values of r and s for the observation well may be substituted in (12), and the resulting expression may be solved for h_w. The computed value of h_w may then be used for the determination of the specific yield. The magnitude of the entrance losses is equivalent to the discrepancy between the computed and the measured drawdowns in the pumped well.

Application to test data from Kearney, Nebraska--To test the practicability of these methods, they were applied to the test data from Kearney, Nebraska, described by WENZEL [1942, pp. 127-131]. The data used for the computation were

Thickness of saturated material = 48 ft
Diameter of discharge well = 25 inches
Q = 1,584,000 gallons per day
s after 24 hr = 3.97 ft for r = 50 ft
s after 24 hr = 2.99 ft for r = 100 ft

The permeability used was 4092 gallons per day per square foot as determined by the limiting formula. When the appropriate values were substituted in (12), it was determined that h_w was approximately 38 ft. Therefore, the drawdown outside the screen of the pumped well was approximately ten feet. As the measured drawdown was 11 ft, the total entrance losses did not exceed one foot. The value of 38 ft for h_w was used in (10). The specific yield computed by this method was ten per cent. This compares reasonably well with the value of seven per cent obtained by Wenzel using the non-equilibrium formula.

It was necessary to compute 60 terms of the series in (10) before the effect of all additional terms became negligible. However, this required only about three hours of computation since the terms of the series are easy to evaluate.

Summary of data requirements--For the successful application of these methods, careful consideration should be given to the following factors.

(1) The total thickness of saturated material, the total pumpage during the test, and the water level in the pumped well and at least one observation well are required.

(2) The period of pumping should be long enough so that the water table has reached equilibrium shape out beyond the observation well and is declining only very slowly. It should be long enough to insure the greatest possible dewatering in the cone of depression, yet short enough so that recharge does not affect the cone of influence.

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GRAVITY MEASUREMENTS AT SEA, 1952 AND 1953

J. Lamar Worzel, G. Lynn Shurbet, and Maurice Ewing

(Lamont Geological Observatory Contribution No. 151)

Abstract--As a continuation of the long-range program of gravity measurements at sea, 489 new measurements were made during 1952 and 1953. In USS Toro (SS 422), USS Corsair (SS 435), and USS Diablo (SS 479), 209 measurements were made in the Atlantic Ocean from the Gulf of Maine to the British West Indies and Puerto Rico. In USS Redfish (SS 395) (two cruises) and USS Bugara (SS 331), 280 measurements were made in the Pacific Ocean from San Diego, California, to the Beaufort Sea with crossings to Hawaii. Instrumental improvements include a clamping mechanism to insure positional control of the light trace indicating tilt of the main pendulum swinging plane and additional level bubbles for observing this tilt.

Introduction--This program of gravity measurements at sea was initiated in 1947 and has been continued through 1953 by the Lamont Geological Observatory of Columbia University [WORZEL and EWING, 1950, 1952; WORZEL, SHURBET, and EWING, 1955]. The purposes of this program

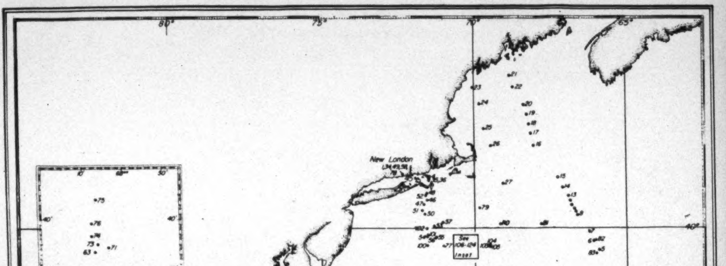


Fig. 1--Gravity at sea, USS Toro (SS 422), January-May, 1952

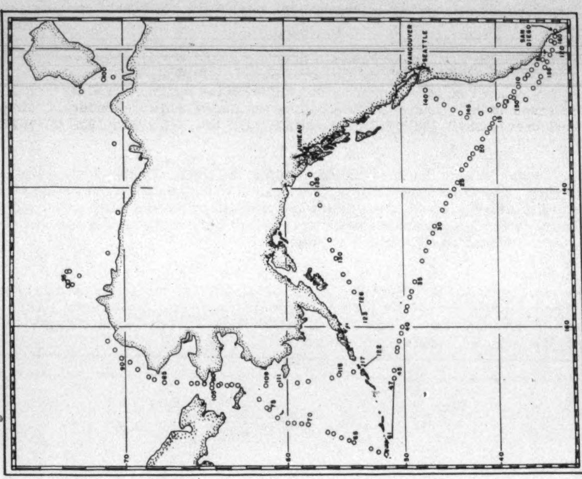

VANCOUVER
SEATTLE
SAN DIEGO
JUNEAU
70
60
50
40
140
160

Fig. 3--Gravity at sea, USS Redfish (SS 395), July-October, 1952

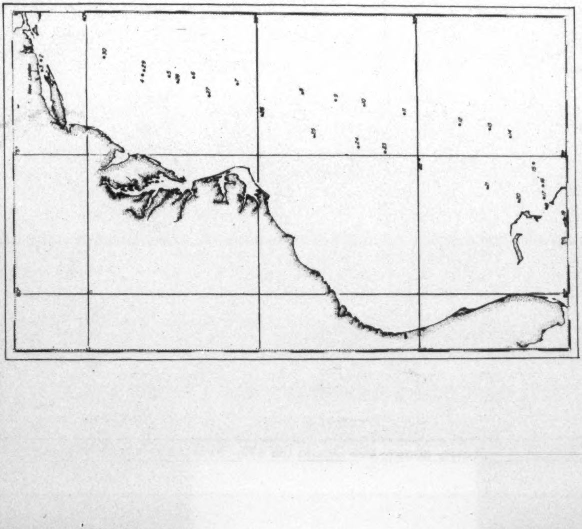


Fig. 2--Gravity at sea, USS Corsair (SS 435), June, 1952 are (1) to establish a network of gravity stations giving broad coverage of the oceans for studies of the figure of the Earth, and (2) to make more detailed gravity surveys in specific areas to study the gravitational field associated with earthquake epicenter belts, continental margins, island arcs, and ocean island areas.

Instrumentation--The basic apparatus used in this gravity program was designed and constructed by VENING MEINESZ [1929]. Data to determine to BROWNE [1937] corrections were obtained with our long-period pendulum apparatus following the design of VENING MEINESZ [1941]. Improvements in the basic apparatus and in auxiliary equipment prior to this period have been described previously [EWING, 1937; WORZEL and EWING, 1950, 1952; WORZEL, SHURBET, and EWING, 1955].

In 1952, it became evident that the prism controlling the position of the β trace (angle of pendulum swinging plane with respect to total acceleration vector) on the photographic record was sometimes shifting during a cruise. This shift was permitted by the mechanical design of the prism adjustment control. A clamping mechanism was installed so that this prism could be fixed in position after the necessary adjustments were made.

At this same time it was decided to install suitable level vials so that even if the β trace were displaced, the levelling would be sufficiently good to eliminate the non-oscillating part of the level correction. The external level bubbles already attached to the equipment were not sufficiently sensitive for this purpose, and were exposed enough so that there was considerable question of their relationship to the level of the knife edge supports.

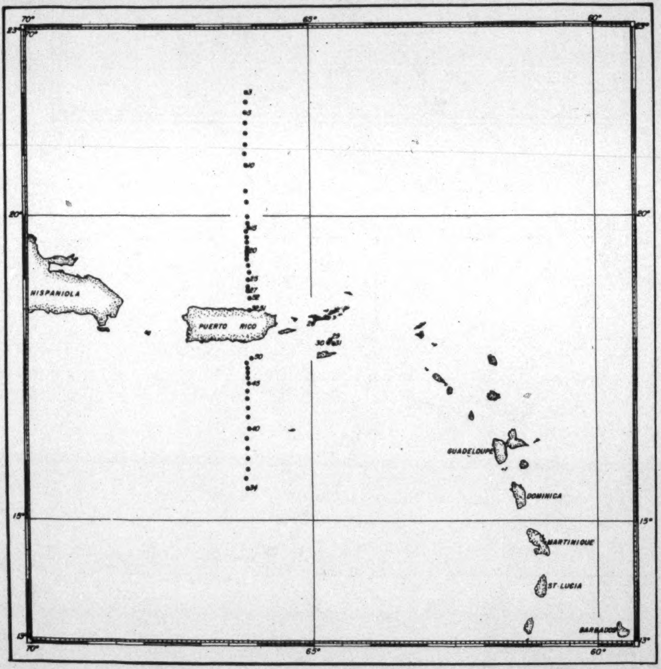


Fig. 4--Gravity at sea, USS Diablo (SS 479), February-March, 1953

Two level vials with a sensitivity of about 50 sec per scale division were obtained and mounted perpendicular to each other and adjacent to the right-hand pendulum support (from the operator's position). These vials have almost the same sensitivity as the precision levels furnished with the equipment. Their bubbles were adjusted to agree with the precision levels when these latter were established on the knife edge flats. Prisms were mounted in the cover of the apparatus so that these bubbles could be observed by the observer when setting the level before an observation and to check the level readings during an observation. Observations have shown that since these modifications the β correction has been negligible in nearly all cases.

Brief description of cruises--From January to May, 1952, 125 gravity measurements were made in USS Toro by G. Lynn Shurbet and J. Lamar Worzel. Measurements were made in the Gulf

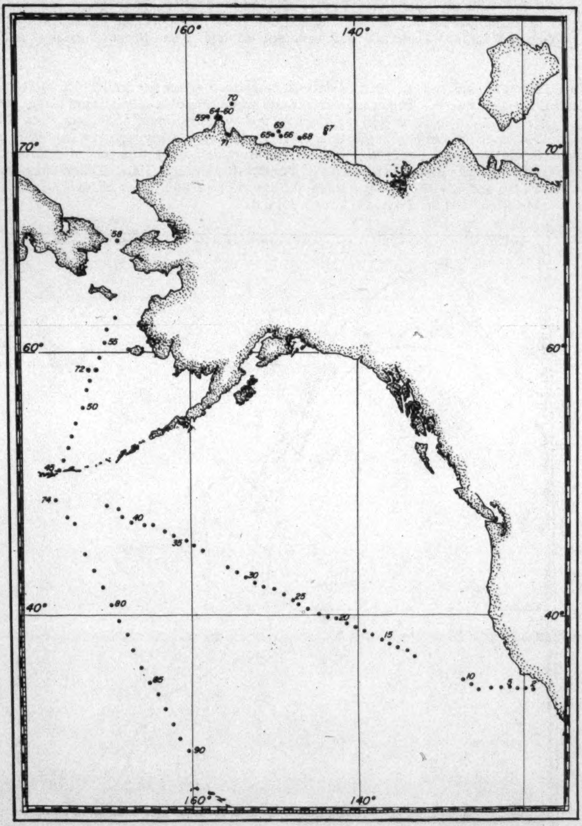


Fig. 5--Gravity at sea, USS Redfish, Cruise II (SS 395), July-September, 1953 of Maine, along the east coast of the United States, and in the area between New London, Connecticut, and Bermuda, British West Indies (Fig. 1). These measurements will add considerably to the knowledge of the gravitational field associated with continental margins and to general coverage of the Atlantic Ocean. Base stations were established in New London and St. Georges, Bermuda.

In June, 1952, 31 measurements were made in USS Corsair by G. Lynn Shurbet and J. Lamar Worzel between New London and Nassau, British West Indies (Fig. 2). These measurements add to the large amount of data already available off the east coast of the United States. Base stations were established in New London and Nassau.

From July to October, 1952, 161 measurements were made in USS Redfish by G. Lynn Shurbet and Hugh Traphagen (Fig. 3). Measurements were made from San Diego, California, through Tanaga Pass, Aleutian Islands, in the Bering, Chukchi, and Beaufort Seas, through Akutan Pass, Aleutian Islands, to Juneau, Alaska, Vancouver, British Columbia, Seattle, Washington, and San Diego. Two crossings of the Aleutian Trench were made and many stations contributing to a broad coverage of the Pacific Ocean obtained. Base stations were established in San Diego, Juneau, Vancouver, and Seattle.

During February and March, 1953, 53 measurements were made in USS Diablo by G. Lynn Shurbet and Hugh Traphagen. These measurements were made on a line from some 200 mi north of San Juan, Puerto Rico, to about 150 mi south of the southern coast of Puerto Rico with a few measurements near St. Thomas, Virgin Islands (Fig. 4). The large negative free-air anomaly associated with the Puerto Rico Trench was well determined along this line of stations. Another large 'gravity trench' was discovered south of Puerto Rico on this line. These data have been reported by WORZEL and EWING [1954]. Base stations were established in New London, Connecticut, San Juan, Puerto Rico, and St. Thomas, Virgin Islands.

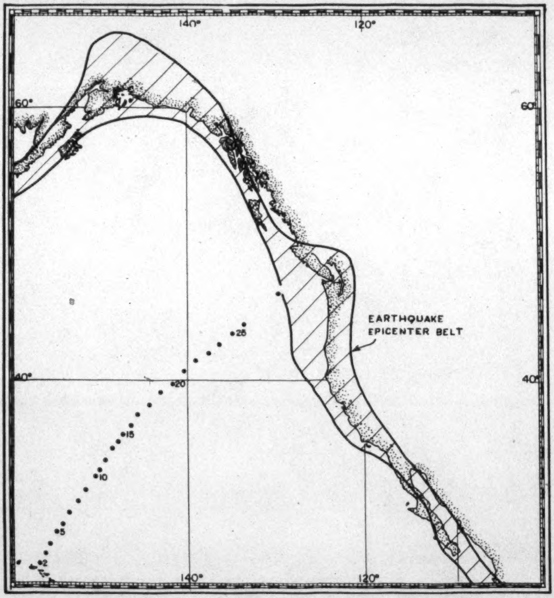


Fig. 6--Gravity at sea, USS Bugara (SS 331), October, 1953

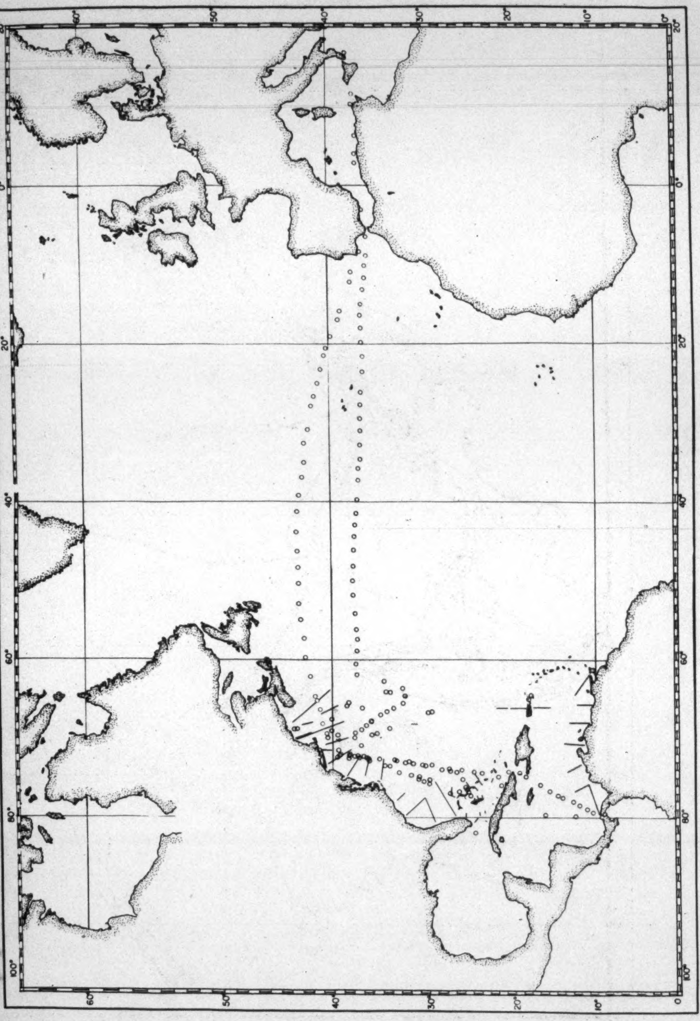

60°
50°
40°
30°
20°
10°
0°
20°
0°
20°
40°
60°
80°
100°

Fig. 7--Gravity at sea, 1947 through 1953

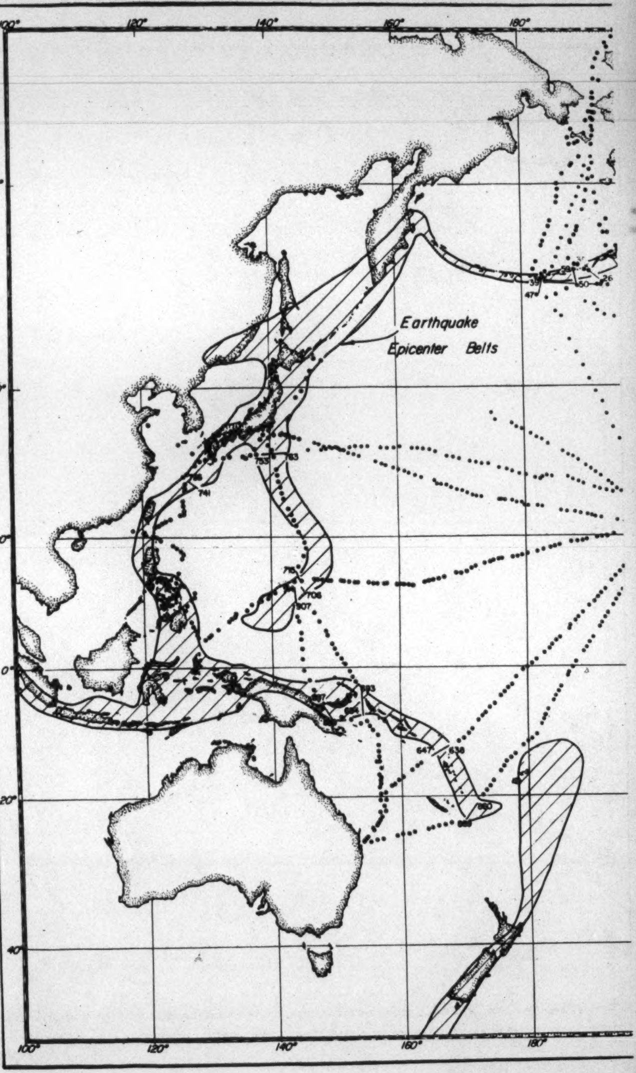
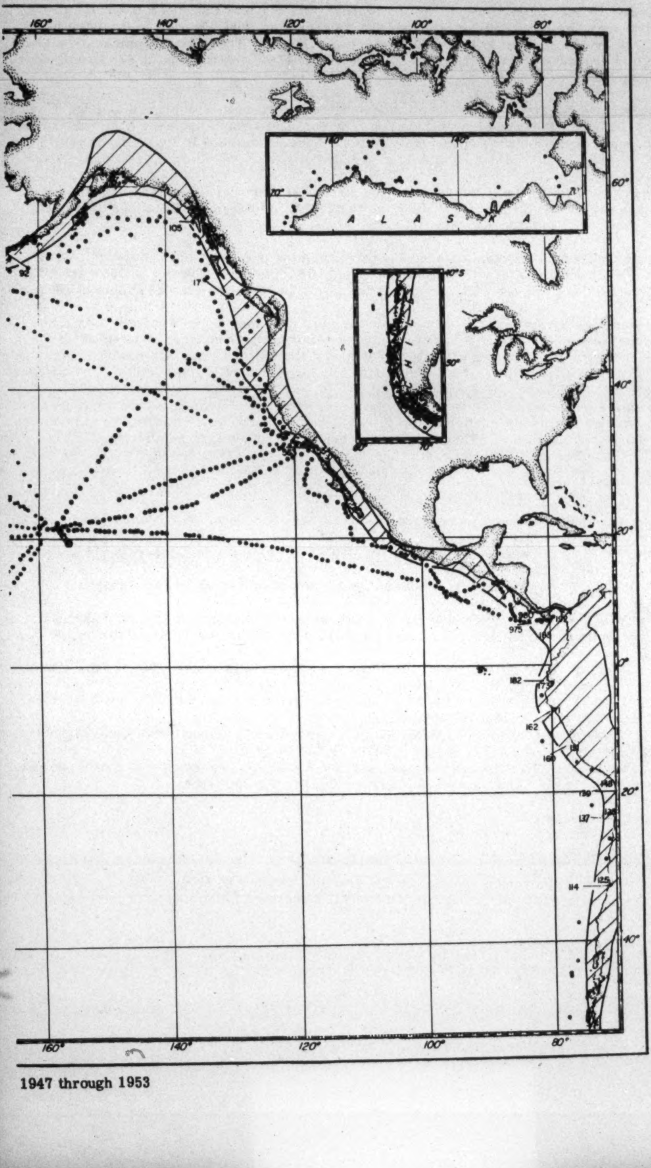

100°
120°
140°
160°
180°
60°
40°
20°
0°
20°
40°
Earthquake
Epicenter Belts
39
47
50
26
741
753
715
706
507
647
638
100°
120°
140°
160°
180°

Fig. 8--Gravity at sea.


160°
140°
120°
100°
80°
60°
40°
20°
0°
20°
40°
A L A S K A
110°
140°
70°
50°
10°
105
17
92
975
182
173
162
160
148
139
137
125
114

1947 through 1953

From July to September, 1953, 91 measurements were made in USS Redfish, Cruise II, by Hugh Traphagen. Measurements were made from San Diego to Adak, Alaska, in the Bering and Beaufort Seas, and from Adak to Pearl Harbor, Hawaii (Fig. 5). These measurements contribute primarily to a broad coverage of the oceans. Base stations were established in San Diego, Adak, and Pearl Harbor.

In October and November, 1953, 28 measurements were made in USS Bugara by Hugh Traphagen from Pearl Harbor to Port Angeles, Washington (Fig. 6). These measurements contribute to the general coverage of the Pacific Ocean. Base stations were established in Pearl Harbor and Port Angeles.

The gravity stations established by this group from 1947 through 1953 in the Atlantic and Pacific Oceans are shown in Figures 7 and 8, respectively. A total of 2057 stations have been occupied.

Free-air and Bouguer anomalies have been computed for USS Tusk and USS Conger, Cruises I and II, in 1947, for USS Argonaut and USS Medregal in 1948, for USS Chopper in 1949, for USS Bergall, Cruise II, in 1950, for USS Toro and USS Corsair in 1952, and for USS Diablo in 1953.

Acknowledgments--Some parts of the apparatus were provided by the Woods Hole Oceanographic Institution and the Naval Ordnance Laboratory, Bureau of Ordnance, Department of the Navy. The cruises were arranged with the assistance of the Chief of Naval Operations, Commander, Submarine Force, Atlantic Fleet, and Commander, Submarine Force, Pacific Fleet. The officers and enlisted men of USS Toro, Corsair, Redfish, Diablo, and Bugara have all cooperated fully to make the cruises successful. The success of the entire program of making gravity measurements at sea is dependent on the cooperation of the U. S. Submarine Force since this work can be done only in a submerged submarine. This program is carried out under Contract N6 onr 271 TO 8 with the Office of Naval Research, Department of the Navy.

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GRAVITY MEASUREMENTS AT SEA, 1950 AND 1951

J. Lamar Worzel, G. Lynn Shurbet, and Maurice Ewing

(Lamont Geological Observatory Contribution No. 150)

Abstract--During 1950 and 1951, 447 gravity measurements at sea were made on five cruises in United States Navy submarines. Gravity observations were made on cruises from San Diego, California, to Pearl Harbor, Hawaii, to Japan and Guam by way of the Philippine Islands and return to Pearl Harbor, from Pearl Harbor to the Canal Zone and New London, Connecticut, and from New London to Taranto, Italy, and return to Norfolk, Virginia. Improvements in the pendulum apparatus include the installation of a more reliable and less expensive light source and the installation of fiduciary markers to provide two reference lines on the photographic records.

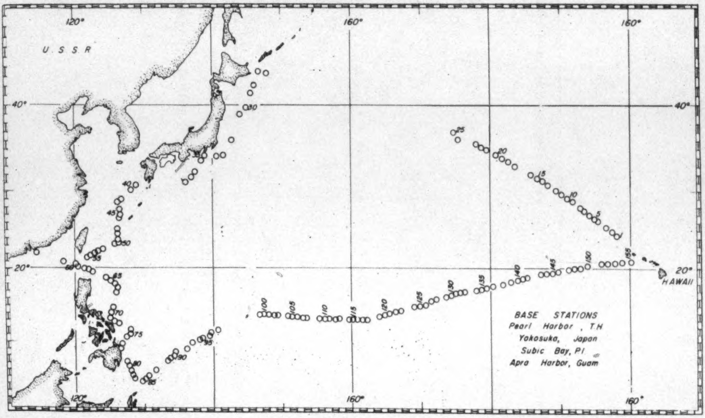
120°
160°
160°
U. S. S. R
40°
40°
20°
20°
HAWAII
30
25
20
15
10
5
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
125
130
135
140
145
150
155
BASE STATIONS
Pearl Harbor, T.H
Yokosuka, Japan
Subic Bay, P.I
Apra Harbor, Guam
120°
160°
160°

Fig. 1--Gravity at sea, USS Sea Dog (SS 401), January-May, 1950

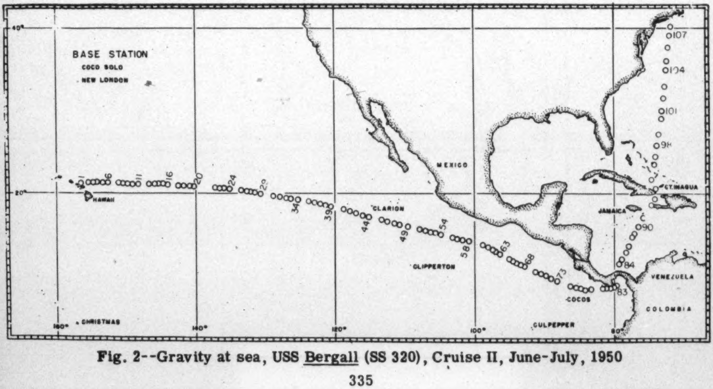
40°
BASE STATION
COCO SOLO
NEW LONDON
107
104
101
98
MEXICO
GT. INAGUA
20°
1
6
11
16
20
24
29
34
39
44
49
54
58
63
68
73
83
84
90
HAWAII
CLARION
JAMAICA
CLIPPERTON
VENEZUELA
COCOS
COLOMBIA
CHRISTMAS
CULPEPPER
160°
140°
120°
100°
80°

Fig. 2--Gravity at sea, USS Bergall (SS 320), Cruise II, June-July, 1950

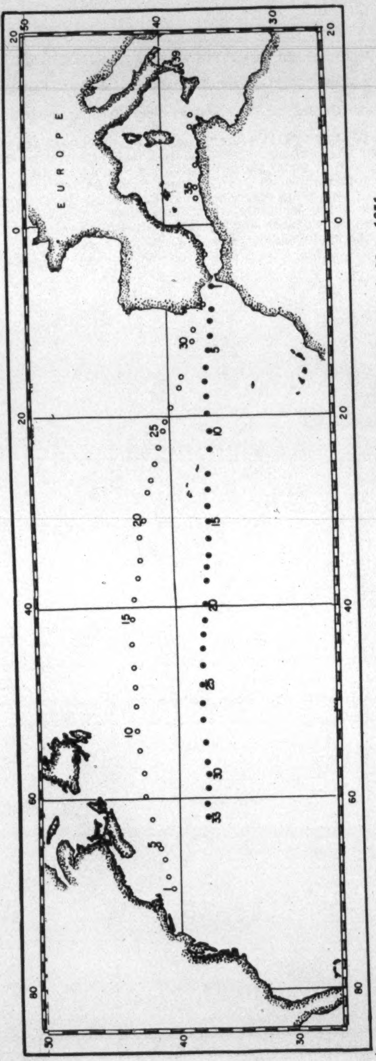
EUROPE
50
40
30
20
0
20
40
60
80
1
5
10
15
20
25
30
35
39
1
5
10
15
20
25
30
33

Fig. 3--Gravity at sea, USS Quillback (SS 424), USS Requin (SSR 481), March-May, 1951

Introduction--The program of making gravity measurements at sea aboard United States Navy submarines initiated in 1947 [WORZEL and EWING, 1950, 1952] was continued during 1950 and 1951 by the Lamont Geological Observatory of Columbia University. The purposes of this long-range program are (1) to establish a network of gravity stations giving a broad coverage of the oceans for studies of the figure of the Earth, and (2) to make detailed gravity surveys in specific areas for studies of the gravitational fields associated with earthquake epicenter belts, continental margins, island arcs, and ocean island areas.

Instrumentation--The pendulum apparatus used during this period is the same one used by EWING [1937] in USS *Barracuda*. The basic apparatus was developed originally by VENING MEINESZ [1929]. Data to determine the BROWNE [1937] corrections were obtained with our long-period pendulum apparatus as designed by VENING MEINESZ [1941]. Improvements in the basic apparatus and in auxiliary equipment prior to this period have been described by WORZEL and EWING [1950, 1952].

In 1950, the apparatus was modified to use an ordinary automobile headlight bulb as a light source. These bulbs give ample illumination, are readily available, inexpensive, and much more reliable than bulbs previously used in the apparatus. They require 6.3 volts AC, a voltage easily obtained in submarines by using a small transformer.

In 1950, fiduciary markers were mounted inside the camera case to place two reference lines on the records, approximately at the center of the fictitious pendulum traces. The lines are produced by scratching the emulsion on the photographic paper with spring loaded metal points.

Brief summary of cruises--Aboard USS *Sea Dog*, during the period January-May, 1950, 160 gravity measurements were made by Shurbet between Pearl Harbor and Japan, by way of the Phillippines to Guam, and Pearl Harbor at positions shown in Figure 1. Measurements were made on ten partial crossings of earthquake epicenter belts in the Nippon Trench and in the Mindanao Deep. The remaining measurements add considerably to the network of stations required for a precise determination of the figure of the Earth. Base stations were established at Pearl Harbor, Hawaii; Yokosuka, Japan; Subic Bay, Philippine Islands; and Apra Harbor, Guam.

Aboard USS *Bergall*, Cruise II, during June-July, 1950, 110 gravity measurements were made by Shurbet between Pearl Harbor, Hawaii, the Canal Zone, and New London, Connecticut, at positions shown in Figure 2. The measurements of this cruise contribute primarily to further broad coverage of the oceans. However, one crossing of the earthquake epicenter belt near Panama and measurements in the Caribbean Sea and the east coast region of the United States were made. Base stations were established in Balboa and Coco Solo, Panama, Canal Zone, and New London, Connecticut.

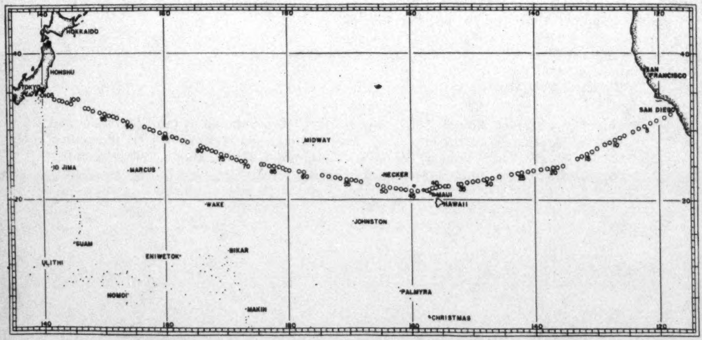

Fig. 4--Gravity at sea, USS *Volador* (SS 490), July-August, 1951

Aboard USS Quillback and USS Requin, during the period March-May, 1951, 72 gravity measurements were made by Shurbet between New London, Connecticut, Taranto, Italy, and Norfolk, Virginia, at positions indicated in Figure 3. These measurements contribute further to the broad coverage of the Atlantic Ocean. A base station was established in New London, Connecticut, aboard USS Quillback and in Norfolk, Virginia, aboard USS Requin.

Aboard USS Volador, during the period July-August, 1951, 105 gravity measurements were made by Shurbet between San Diego, California, Pearl Harbor, Hawaii, and Japan at positions indicated in Figure 4. These measurements contribute principally to broad coverage of the Pacific Ocean. A partial crossing of the earthquake epicenter belt near Yokosuka, Japan, was made. A base station was established at Pearl Harbor, Hawaii. The equipment was returned to Pearl Harbor from Japan in USS Queenfish (SS 393); however, because of the failure of the crystal chronometer, no gravity measurements were made.

The report of gravity measurements at sea during 1952 and 1953 appearing in this same issue contains summary maps (Fig. 7 and 8) of all measurements at sea by this group from 1947 through 1953.

Acknowledgments--Some parts of the apparatus were provided by the Woods Hole Oceanographic Institution and the Naval Ordnance Laboratory, Bureau of Ordnance, Department of the Navy. The cruises were arranged with the assistance of the Chief of Naval Operations, Commander, Submarine Force, Atlantic Fleet, and Commander, Submarine Force, Pacific Fleet. The Officers and enlisted men of USS Sea Dog, Bergall, Quillback, Requin, and Volador have all cooperated fully to make the cruises successful. The cooperation of the U. S. Submarine Force is essential to the success of the entire program of making gravity measurements at sea since this work can be done only in a submerged submarine. This program is carried out under Contract N6 onr 271 TO 8 with the Office of Naval Research, Department of the Navy.

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DISCUSSION OF

"SOME MEASUREMENTS OF ABLATION, MELTING, AND SOLAR ABSORPTION ON A GLACIER IN PERU"

by WALLACE E. HOWELL

[Trans., v. 34, pp. 883-888, 1953]

David H. Miller (Environmental Protection Division, Quartermaster Research and Development Command, Natick, Mass.)--Howell's paper shows a commendable concern with evaluating some of the thermal processes that produce snow melt, but omits several other components of the total energy balance. In equating snow melt to absorption of insolation, he neglects the heat lost by long-wave radiation, which is large at the elevation of the snowfield he observed, more than 4000 m above sea level, and also the heat gained by convection. It is true that the air over the snow probably had been heated by contact with sun-warmed rocks in the local environment, so that convection had the role of intermediary rather than being an agent of large-scale advection, but this local flow of heat from rocks to snow is important in the total heat budget. The thermal balance of snow has been extensively studied by the Corps of Engineers, and from preliminary equations developed in their Civil Works Investigations Project CW-171, I estimate convective heat flow in the middle of the second, more sunny, day of Howell's observations to be about ten calories per square centimeter per hour. The loss of heat by net long-wave radiation can be estimated, from measurements over snow at lower elevations in the Sierra and Cascades, at about the same amount. These measurements were made at sites at which a fraction of the hemisphere, as at the Andean sites, is occupied by rock and snowfields. Evaporation from the snow surface probably required about four calories per square centimeter per hour. On the other hand, it is likely that absorption of radiant energy by the snow was slightly larger than he estimated from measurements of albedo in the visible range, when applied to the total spectrum.

From the observations he gives, I reconstruct the approximate midday heat balance during a midday hour, October 11, as follows:

	cal/cm^2
Absorption of solar radiation (direct and diffuse)	36
Advection of sensible heat from rocks to snow	10
Net loss of heat by long-wave radiation	- 8
Loss of heat by evaporation	- 4
Heat consumed in melting snow	- 34

In the situation Howell describes, omission of the three smallest modes of heat transfer does not produce great error, but in other sites where the local environment is different it is preferable to include all components of the energy budget. In the mountains of the western United States, for example, although insolation is smaller than in the Andean site, the rate of snow melt is about double, partly because of differences in the three other components of the budget caused by differences in the physical geography of the region.

Wallace E. Howell (Wallace E. Howell Associates, 634 Massachusetts Ave., Cambridge, Mass., Author's closure)--Miller has made an interesting and intelligent attempt to construct a heat budget, but I am inclined to suggest some revisions of it.

The net radiative heat transfer was affected by the considerable fraction of the apparent hemisphere occupied by nearby rock and snowfields and by distant lowlands. The incoming radiation from these sources makes the net loss certainly smaller than Miller's estimate, possibly very much smaller.

The only net advective heat transfer is that due to the excess of wet-bulb temperature above the melting point; the rest of the advected heat is carried away by the air as latent heat of evaporated water. The wet-bulb excess was only about a sixth the dry-bulb excess during the noontime hour for which the budget was drawn.

I would suggest a budget during midday hour, October 11, as follows:

	cal/cm^2
Absorption of direct solar radiation	32
Net long-wave and indirect short-wave radiation	0
Advection	14
Evaporation	- 12
Melting	- 34

I can well appreciate that the symmetry of this budget is peculiar to the glacier where the measurements were made, and one would soon be in trouble assuming such symmetry to be general.

DISCUSSION OF

"FREE-SURFACE INSTABILITY OF LIQUIDS IN STEEP CHANNELS"

by MELVILLE S. PRIEST and ALY BALIGH

[Trans., v. 35, pp. 133-135, 1954]

I. M. Mostafa El Assiouty (State University of Iowa, Iowa City, Iowa)--Boundary-layer phenomena have important effects upon the flow conditions under which the free surface of liquids in steep channels becomes unstable. A diagramatic sketch of the process of developing the boundary layer in steep channels is shown in Figure 2. Figure 2a indicates that a boundary layer begins to develop at the entrance where the velocity is essentially constant and expands gradually until the layer meets the free surface. From this section on the flow is uniform having a parabolic velocity distribution of the established laminar motion. If the Reynolds number is sufficiently high, the boundary layer will become unstable before this section is reached (Fig. 2b) and further growth takes place in accordance with the principles of the turbulent boundary layer.

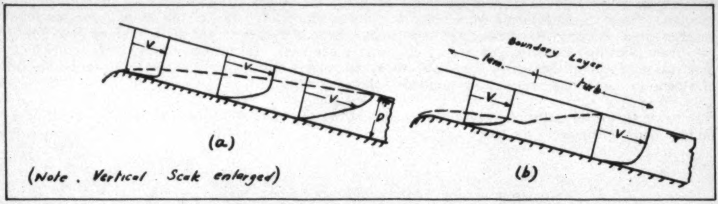

Fig. 2--Development of the boundary layer in a steep channel

The established flow is inherently laminar in nature for values of $R \leq 500$, in which R is defined as UD/ν and U = mean velocity, D = depth of flow, ν = kinematic viscosity. Beyond this value, either a laminar or a turbulent flow is established depending upon the nature of the disturbance present in the flow. For an established laminar flow, a relationship can be shown among the Reynolds number, the Froude number, and the inclination of the channel bottom. The expression of this relationship

$$S = 3\mu U/\gamma D^2 = 3F/R$$

is derived from the expression for flow between two parallel plates, where S is the sine of the angle of inclination of the channel bottom to the horizontal, $F = U^2/gD$, and $R = UD/\nu$. A logarithmic plot of this relationship is shown in Figure 3. On the same diagram the corresponding experimental data, as obtained by the authors, are plotted. Those data tend to follow the curves obtained from the aforementioned expression. The divergence of some of the experimental data from these curves may be the result of the difficulty in measuring the flow depth upstream from

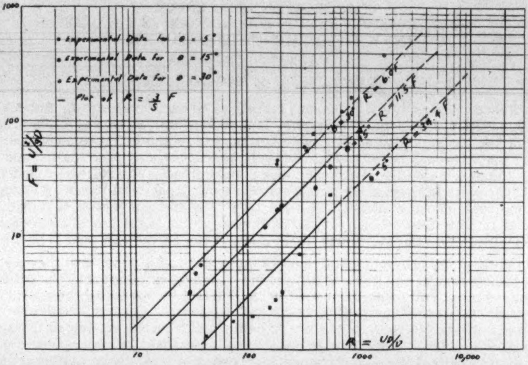

Fig. 3--Relationship between the Reynolds number and the Froude number for different inclinations of channel bottom

the initial instability in supercritical flow. It also appears from Figure 3 that the authors' statement, "The curves approach a common limiting curve at the lower value of UD/ν and U^2/gD," is not sound.

This paper would have been even more useful had the authors investigated the characteristics of the flow downstream from the initial instability. Since in this case the flow cannot be defined by the Reynolds and the Froude numbers alone, a wave number, given in the form $2\pi D/L$ in which D = depth of flow, and L = wave length, must be introduced. The stability of parallel laminar flow with respect to wave formation at the free surface has been investigated by YIH [1954]. He found that for the neutral stability a relationship between the Reynolds number and the wave number can be obtained for any given slope of the initiated flow by the Sommerfield - Orr equation. Yih's paper is a valuable reference for a better understanding of this subject.

Reference

YIH, C. S., Stability of parallel laminar flow with a free surface, presented at the second National Congress of Applied Mechanics, Ann Arbor, Michigan, June, 1954.

Melville S. Priest and Aly Baligh (Cornell University, Ithaca, N. Y., Authors' closure)--In his discussion, Mostafa refers to a particular relation between a Fronde number, a Reynolds number, and sine of the angle of inclination of the channel bottom to the horizontal. This is nothing more than a relation that has been developed for a particular case of uniform, viscous flow. Nevertheless, it appears that he considers this relation to be a suitable criterion for free-surface instability, in general. There is no evident reason why the curves on Figure 1 of the paper should conform to this relation. The significance of Figure 1 should be kept in mind. If conditions were those of uniform flow, there would be no data to plot on that figure. The study was not concerned with degree of proximity to uniform flow conditions, nor was it limited to viscous motion.

Further, it seems appropriate to point out that the problem of describing the flow characteristics downstream from initial instability should not be underestimated. A general quantitative analysis of flow characteristics that may exist would encompass both wave motion and air entrainment. Although a number of investigators have considered particular aspects of the problem, much remains to be done. It is a simple matter to state the need for additional information, but seldom simple to acquire it.

DISCUSSION OF
SYMPOSIUM ON LAND EROSION
"SOME OBSERVATIONS ON SOIL EROSION IN THE MIDDLE AND EASTERN MEDITERRANEAN AREA"
by MARTIN R. HUBERTY

[Trans., v. 35, pp. 244-246, 1954]

M. Rim (Hebrew University, Jerusalem, Israel)--The caption chosen by Huberty for his photograph of the Jerusalem limestone hills implies that ancient Roman conservation practices were responsible for the accumulation of cultivable soil covers on the terraces shown on the picture, most of it lost since through neglect and leaving the terraces today practically bare limestone rock. Such a Roman accomplishment would appear to contradict the statement made by Huberty in the same paper as to the negligibly small soil-creating capacity of those limestones (25 parts of limestone to create one part of mineral soil), as well as his assumption that overland erosion and the mobility of soil material are very limited since in the karst limestone formations most rainwater is drained away internally and little, if any, runs off the surface.

Actually the terraces shown are not 'ancient terraces' in the sense that they were hewn into the hard limestone rocks by the Romans but are natural bedding terraces. The lower-level terraces were indeed made cultivable by ancient agriculturists by bordering them with stones, thus impounding runoff and washed-down eroded soil. (The latter was essential, at a time when chemical fertilisation was unknown, to rejuvenate the soil continuously on the cultivated terraces, apart from building up soil depth.) Since this process, for the reasons correctly pointed out by Huberty, was too slow to be practical, those cultivators enhanced it artificially by deliberately initiating soil erosion on the upper portions of these naturally terraced hills by erecting there rubble stone walls that ran straight or obliquely down the hill to lead runoff water and eroded soil material onto the cultivated terraces and patches in the valley. One such wall can be faintly discerned on the discussed photograph (cutting off the right bottom corner of the picture at 45° about midway between the corners).

Only in the less arid portions of the region discussed--in the northern part of Israel and in the Lebanon--could these natural bedding terraces of the limestones be utilized right up to the hilltops; in the more arid portions--the limestone hills bordering the Sinai desert--the ancient cultivators covered the whole extent of the slopes with an elaborate, most impressive system of structures designed to hasten and intensify rain water runoff and wash-down of soil material to be impounded and put to use in the cultivated valleys. The overland erosion rate for the karstic limestone hill region of Israel has been determined by the writer to come up to almost one millimeter per annum, including limestone dissolution. The ratio of soil formed to limestone dissolved indicated by Huberty should be thought to be of too small a magnitude to hold on a geologic scale: karstic limestones are much dissected by soil-filled crevices, contain many clay lenses and are intercalated with geologically identifiable marl and loam layers, all abundant suppliers of soil material. In fact, not far from the spot photographed by Huberty is Jerusalem's brick factory which is using these clays and loams as raw material.

Martin R. Huberty (University of California, Los Angeles, Calif., Author's closure)--Rim has given a very good account of the manner in which soil was added to the modified bedding terraces on the hills near Jerusalem, but he has read into the title of Figure 2, 'Ancient terraces on limestone hills near Jerusalem, Israel,' a sequence of erosion events that was not envisioned by me when I wrote the title, nor as I reread it.

The statement that the composition of some of the limestone rock is such that it would require at least 50 cu ft of rock to contribute two cubic feet of mineral soil refers particularly to the highly karstic formations in Yugoslavia. The information was obtained from a staff member in the University of Belgrade.

DISCUSSION OF

SYMPOSIUM ON LAND EROSION
"PIPING"
by JOEL E. FLETCHER, KARL HARRIS, H. B. PETERSON, and V. N. CHANDLER

[Trans., v. 35, pp. 258-262, 1954]

L. A. Heindl and J. H. Feth (U. S. Geological Survey, Water Resources Division, Tucson, Ariz.)--The present writers are familiar only with the Picacho and San Pedro areas, among those cited by the authors, and therefore limit discussion to the occurrence of earth cracks in these areas.

The existence of piping is not questioned, and the five conditions suggested by the authors are a justified explanation in the San Pedro area, for example. It is thought, however, that some of the phenomena described as piping are earth cracks whose origins are governed by factors other than those outlined. Once formed, certain earth cracks may facilitate the development of piping by providing ready access to downward and lateral movement of water.

In discussing the Picacho area, the authors state, "at points where these (pipes) intersect the highway and railroad they appear to be large cracks in the soil surface." This implies that they do not appear as large cracks elsewhere. In 1949 the writers and O. B. Coulsen observed earth cracks in the Picacho area both crossing the highway and railroad and crossing untrenched flood plains and McLellans Wash, the largest drainage system in the area (Fig. 15). The cracks existed as cracks even where they do not cross thoroughfares. Nor were the earth cracks observed to pass into pipes. Rather, they lost their identity gradually, in one case disappearing in a maze of mud cracks. Characteristically, the bottoms of the cracks, where they could be observed, bore no resemblance to a channel or pipe and showed no signs of open drainage.

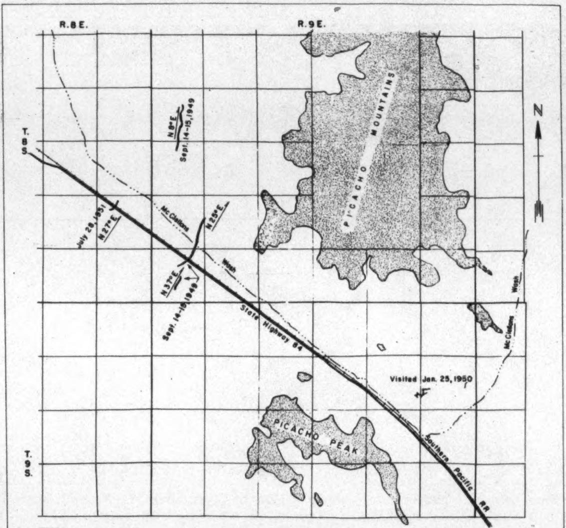
R.8E.
R.9E.
T. 8 S.
T. 9 S.
N
PICACHO MOUNTAINS
N8°E
Sept. 14-15, 1949
July 28, 1951
N27°E
McClellans
N25°E
Wash
N37°E
Sept. 14-15, 1949
State Highway 84
Wash
McClellans
Visited Jan. 25, 1950
PICACHO PEAK
Southern Pacific RR
Areas of exposed rock
1
0
2 Miles
Earth-fissure

Fig. 15--Sketch map of a part of Red Rock Quadrangle, Arizona, showing locations of earth fissures in the vicinity of Picacho Peak, Arizona

A possible exception to the foregoing conditions is found in the reticulate cracks shown in the southeastern part of the area (Fig. 15). This series was shallower and much less linear in plan than those west of Picacho Peak and Picacho Mountains.

The authors also state, "the pipes extend from several playa-like areas toward a shallow entrenched drainage way," and that "the so-called cracks all extended from one or more of the playa-like areas to the entrenched drainage way near the center of the piping area." This implies that the earth cracks had some sort of drainage-controlled pattern.

Figure 15 shows part of the Red Rock Quadrangle, Arizona, including the area in which the earth fissures of 1927, 1949, and 1951 occurred. According to Eldred D. Wilson of the Arizona Bureau of Mines [FETH, 1951, p. 25], the fissure that crossed the highway in 1949 opened at essentially, if not identically, the same place as that of 1927 [LEONARD, 1929]. It was partly reopened in 1951. Figure 15 shows certain features not indicated by the authors which are believed to require an origin other than those suggested for piping. The southernmost and northernmost of the 1949 cracks and the single 1951 crack had no entrenched drainageway that anywhere approached the maximum depth (10 to 15 ft) of the crack itself. If the cracks were the result of piping, they had somehow cut to below the base level of their control.

The five postulates proposed by the authors for piping do not explain the following items in the case of the earth cracks in the Picacho area: (1) the linear extent of the cracks, about one mile in each of two cases, (2) the subparallel alignment of the earth cracks with the adjacent mountain masses, (3) the difference in appearance between the pictured 'pipes' and the earth cracks in Figure 16, and (4) the relative scarcity of earth cracks when true piping in alluvial materials is widespread.

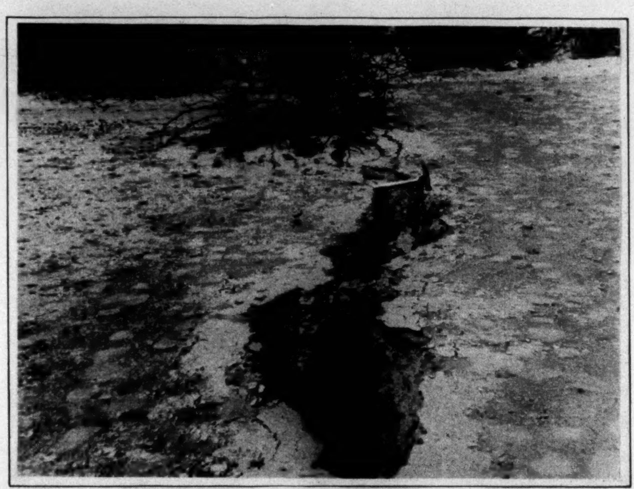

Fig. 16--Near view of a portion of the earth cracks of September 14-15, 1949, directly north of McClellans Wash; photograph taken September 30, 1949, by L. A. Heindl and O. B. Coulsen

Furthermore, it seems significant that the fissures become nearly filled in the course of about a year, indicating that there is not free discharge, as into an "outlet for the lateral flow." Instead, the partial filling suggests that there is no ready outlet for lateral flow. This is particularly significant where the earth crack crosses McClellans Wash. The "succulence and size of the desert vegetation" apparently reflect the capacity of the filled earth fissures to accumulate and store moisture beyond the storage capacity of the surrounding, unfissured terrain.

In the Picacho area, a suggested origin of the earth cracks is based on the following observations: (1) their length and parallelism to the mountain fronts, (2) their clean walls, sharp edges, and lack of displacement when fresh, and (3) their occurrence after heavy summer storms. In 1949, S. F. Turner, then District Engineer, Ground Water Branch, Tucson, Arizona, suggested the possibility that "the fissuring resulted from strains set up by subsidence of unconsolidated and weakly consolidated valley-fill materials off the edge of the buried pediment" [FETH, 1951, p. 26]. The clean walls and sharp edges suggest tensional breaks, which may be the result of differential settling along the edge of a concealed pediment marking a fault line or buried fault-line scarp.

The relation of the heavy summer storms to the fissuring may be more than coincidental. It may result in differential loading of sediments on either side of the possibly concealed pediment edge or in the reduction of bearing strength so as to permit movement, or both. However, equally heavy summer storms occur without accompanying fissuring, and it remains to be demonstrated that heavy precipitation could penetrate rapidly enough to have an effect within a few hours.

In the San Pedro area, several earth cracks are a few hundred feet long. Individual cracks are relatively straight and are roughly parallel to the course of the San Pedro River. They are underlain by coarse gravels which may represent buried former channels of the San Pedro River. The conditions there fit those proposed by the authors.

References

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LEONARD, R. J., An earth fissure in southern Arizona, J. Geol., v. 37, pp. 665 and 773, 1929.

Joel E. Fletcher (U. S. Agricultural Research Service, Tucson, Ariz., Authors' closure)--It should be pointed out that it was not the intent of the authors of this paper to deny the presence of or describe true earth cracks which were presumed to be present in three of the areas studied. It was the intent rather to point out the conditions necessary for the phenomenon of piping to occur.

During the study of the Picacho area the criterion used to assure us that we were studying true pipes ('so-called cracks') and not the 'cracks' mentioned by Heindl and Feth was the continuity of soil horizons across the bottom of a tunnel. Where these layers were discontinuous the particular tunnel was abandoned as of questionable origin.

DISCUSSION OF

"RIVER DEPLETION RESULTING FROM PUMPING A WELL NEAR A RIVER"

by ROBERT E. GLOVER and GLENN G. BALMER

[Trans., v. 35, pp. 468-470, 1954]

Mahdi S. Hantush (Geophysics Department, University of Utah, Salt Lake City, Utah)--In addition to the notation used by the authors, the following is also used:

b = the thickness of the artesian aquifer, ft
b' = the thickness of the confining bed through which vertical leakage takes place in proportion to the drawdown, ft
K' = permeability of the confining bed, ft/sec
T = transmissibility of the aquifer which is equal to Kb in confined flow systems, and equals KD in unconfined flow systems, ft/sec
S = storage coefficient which, in artesian aquifers, is the volume of water that a unit decline of head releases from storage in a vertical prism of the aquifer of unit cross-section; its ultimate value in water table aquifers is the specific yield of the aquifer, which is designated by V in the authors' paper, demensionless
B = leakage factor, which equals $\sqrt{Tb'/K'}$ ft [HANTUSH and JACOB, 1954]
$\mathrm{erf}(Z)$ = the error function or the probability integral = $(2/\sqrt{\pi})\int_0^Z e^{-v^2}\,dv$
$\mathrm{erfc}(Z)$ = the complementary error function = $1 - \mathrm{erf}(Z)$

This paper is a valuable piece of work in the field of hydrology. The authors did not discuss fully the result of their valuable work. The following points are therefore to be observed:

(1) The authors' Eq. (4) is basically for artesian aquifers, although it is used in water-table aquifers with certain limitations. Thus the result obtained by the authors is basically for artesian aquifers and, therefore, can be used without limitations provided, of course, the assumptions made in deriving (4) are met.

(2) Under water-table conditions, (4) is valid if $s/D \leqq 0.02$ [JACOB, 1950, pp. 376-377]. It can be shown that if the left side of (4) is replaced by $(s-s^2/2D)$, then the resulting expression is valid for $s/D \leqq 0.25$, provided that the storage coefficient remains constant [JACOB, 1950]. If the authors' analysis, or a slightly different one, is applied to the new modified equation, the final result will be identical to that of the authors' (12). Hence, under water-table conditions, (12) is valid for $s/D \leqq 0.25$ provided the storage coefficient is constant.

(3) To maintain a uniform head over the river, the authors applied the method of images on the equation for discharge (11) rather than on the equation for drawdown (4). While this approach is absolutely correct, it not only leaves the potential distribution in the aquifer unknown, but it necessitates also reducing the resulting complicated expression to a form suitable for computation, a process that may be avoided if the potential distribution for a particular problem is known. In the present problem the expression resulting from applying the method of images on the discharge equation is simple and needs no further reduction, in which case no particular advantage is obtained by basing the analysis on an already known potential distribution. However, one may be confused as to why the well should be imaged by the river bank when the total discharge across the river is independent of the position of the recharging well so long as the well is located on a line x_1 distant from and parallel to the river. The drawdown at the line x_1 remains zero only if the velocity induced by the recharging well at every point of the line x_1 is equal to that induced by the discharging well.

Potential distributions in several flow systems of different boundary conditions have been worked out [THEIS, 1941; HANTUSH and JACOB, 1954, 1955abc]. These developed solutions afford ready expressions which when combined with the generalized Darcy's Law make possible the computation of the quantity of flow through any section of the flow system.

(4) It may be of interest to mention here that a more general solution that takes into consideration the effect of leakage into the aquifer and of which (12) is a special case (leakage is zero) can be obtained by the same or a slightly different procedure from that followed by the authors.

The drawdown produced by the flow to a steadily discharging well located near a fairly long straight stretch of a river that cuts through an artesian leaky aquifer is given by HANTUSH and JACOB [1955b].

$$s = (Q/4\pi T)\int_1^{\infty} (e^{-u_1 v} - e^{-u_2 v})\,(e^{-w/v}/v)\,dv \quad \ldots\ldots\ldots\ldots\ldots \quad (13)$$

where $u_1 = [(x - x_1)^2 + y^2]\,S/4Tt$, $u_2 = [(x + x_2)^2 + y^2]\,S/4Tt$, and $w = Tt/SB^2$. Leakage into or out of the artesian aquifer is assumed vertical and in proportion to the drawdown [JACOB, 1946].

If (13) is combined with the generalized equation of Darcy, namely, $q = K\int_A (\partial s/\partial x)\,dA$, the quantity of water drawn from the river will be given, after mathematical reduction, by the following relation

$$q = (Q/2)\,[e^{x_1/B}\,\mathrm{erfc}\,(\sqrt{x_1^2 S/4Tt} + \sqrt{Tt/SB^2}) + e^{-x_1/B}\,\mathrm{erfc}\,(\sqrt{x_1^2 S/4Tt} - \sqrt{Tt/SB^2})] \quad \ldots\ldots\ldots\ldots\ldots \quad (14)$$

When there is no leakage $[(1/B) = 0]$, (14) will reduce to (12).

Although (13) and (14) are developed for artesian condition, they can be used also for water-table conditions provided that the limitations discussed under item (2) above are met.

References

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HANTUSH, M. S., and C. E. JACOB, Non-steady radial flow in an infinite leaky aquifer, Trans. Amer. Geophys. Union, v. 36, pp. 95-100, 1955a.

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JACOB, C. E., Radial flow in a leaky artesian aquifer, Trans. Amer. Geophys. Union, v. 27, pp. 198-205, 1946.

JACOB, C. E., Engineering Hydraulics, Chapter 5, John Wiley and Sons, 1950.

THEIS, C. V., The effect of a well on the flow of a nearby stream, Trans. Amer. Geophys. Union, pt. 3, pp. 734-737, 1941.

Robert E. Glover and Glenn G. Balmer (U. S. Bureau of Reclamation, Denver Federal Center, Denver 2, Colo., Authors' closure)--It is gratifying that Hantush has been able to develop a more general solution than that obtained by the authors, and to confirm the special case treated by them.

In regard to his question about the position of the image well, this well may be placed anywhere along the line he describes, and it will ultimately cause the total well flow to cross the line representing the position of the stream. However, the only line along which the drawdown will remain at zero is a straight line drawn midway between the pump well and the recharge image well and at right angles to the line joining them. Since the stream maintains the condition of zero drawdown along the near bank, the line of zero drawdown, described above, must coincide with it, and this fixes the position of the image well.

DISCUSSION OF

"THE TRANSMISSION OF WATER THROUGH SNOW"
by R. W. GERDEL

[Trans., v. 35, pp. 475-485, 1954]

Walter T. Wilson (U. S. Weather Bureau, Washington 25, D. C.)--For several years Gerdel has been a leader in reducing snow lore to a science. He has helped identify the important physical elements that define snowpack condition, and has made important contributions to their measurement. In this paper he has shown the prevailing and limiting values of characteristics relating to the storage and movement of liquid water. There should remain little doubt that a snowpack seldom retains very much liquid water and that liquid water ordinarily moves very rapidly through a snowpack.

In addition to using what appears to be a complete set of physical measurements of snowpack properties, Gerdel refers to a snowpack in terms of its ripeness. Perhaps this is a symbol of his familiarity with snow as a natural substance in the field as well as a laboratory subject. Gerdel does not say how a person lacking long and intimate experience with snow can tell when it is ripe; in fact he asserts that the term is hard to define. He gives a few hints, though, in disclosing that ripe snow may have a wide range of density, but the grains must be coarse and the structure must be uniform. Later in his paper he appears to be less sure of the importance of uniformity of structure because he discusses drainage channels and ice layers in ripe snow. Other writers have attempted to make the term less esoteric by reference to threshold values of density, temperature, and liquid-water content. But there is disagreement as to the critical value of the various physical elements and even as to the particular element or combination of them that define snow ripeness.

The term ripe implies a stage in the metamorphosis of a snowpack connoting its readiness to participate in hydrologic processes. Prior to this stage the snowpack is relatively inert: it stores heat and water but does nothing to the rest of the hydrologic system. Consideration of the thermal constants of snow shows that the quantity of heat required to bring snow to a reasonable threshold of temperature is rather small in comparison with the vast amount of heat required to melt it, and also in comparison with the errors in measuring the rate of heat supply. Gerdel has shown that a snowpack is ordinarily so permeable to water that a threshold value of water content is small in contrast with the error inherent in ordinary methods of measuring it. These facts seem to diminish the validity of the idea that entering the ripe stage involves important quantities of energy or water. The extreme variability of snowpack properties even over small areas and short periods of time reduces still further the practical value of the concept of an expanse of snow passing from one stage to another that is critically and definably different. If the term ripe with respect to snowpack is to persist it would seem that those who use it in scientific literature have an obligation to publish a definition in terms of reproducible physical measurements. Failure to do this might possibly result in a spectrum of colorful terms, such as rotten water coming from over-ripe snow, or snow being known as green before it becomes ripe.

R. W. Gerdel (Snow, Ice, and Permafrost Research Establishment, Wilmette, Ill., Author's closure)--In criticizing the use of the word ripe to define an actively discharging snowpack, Wilson appears to be raising a question of semantics rather than of terminology.

In place of the antonyms green and rotten suggested by Wilson as being inappropriate, the word immature might well be applied to an unripe snowpack which has reached its seasonal maximum water equivalent content but which is not morphologically or thermodynamically ready to participate in the hydrologic cycle.

Wilson has defined the word ripe for us by pointing out that "Prior to this stage the snowpack is relatively inert." We could perhaps improve this definition by substituting immature for inert since a ripe snowpack may be inert during periods when there is insufficient heat for melting.

The lack of uniform distribution of ripeness over even small areas of a snow-covered watershed is analogous to the lack of uniform ripening of a field of grain, and yet, as the farmer knows when the grain is ready for harvest, so apparently does the snow hydrologist recognize when a field of snow is ripe and ready to participate in the hydrologic process. Ripeness appears to have been given the sanction of good usage by such authors as Wisler and Brater (Hydrology, p. 136), Johnston and Cross (Elements of Hydrology, p. 52), and Linsley, Kohler, and Paulhus (Applied Hydrology, p. 139). Although long circulation does not give integrity to a counterfeit coin, repeated usage soon results in acceptance of a word or new definition for a word, even by some of us who may only condone rather than approve of it.

DISCUSSION OF

"GEOSYNCLINES"

by W. WERENSKIOLD

[Trans., v. 34, p. 776, 1953]

W. Armstrong Price (Department of Oceanography, A and M College of Texas, College Station, Texas)--Werenskiold's hypothesis requires that a 'great supply' of sediment be available for the filling of deep oceanic troughs off some sectors of the young Tertiary mountain ranges of the Pacific borders. He postulates that the sediment came from or through these ranges. The writer has been in the habit of explaining the absence or small development of coastal plains and continental shelves off such ranges as due to the small volumes of sediment coming from or through the mountains in relation to the abundance of sediment from continental interiors or mountains fronted by a broad piedmont belt or broad coastal plain already formed. The time factor also must, of course, be considered.

The immature development of coastal plains and continental shelves off young mountain chains may be attributed in part, if we follow Werenskiold's hypothesis, to the necessity for marginal oceanic troughs to be filled first. However, it is too early to revise comparisons between sediment loads delivered from the flanks of coastal mountain chains and those from continental interiors until we can determine to what extent Ewing's (Turbidity-current transportation of sediments in the Atlantic, abstract, Program, 1953 An. Meeting, Geol. Soc. Amer., pp. 53-54) conclusions on the filling of the Puerto Rican trough by turbidity-flow sediments derived from great distances may apply to other oceanic troughs.

REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

RANKAMA, KALERVO, Isotope Geology, McGraw Hill Book Co., New York; Pergamon Press, Ltd., London, 535 pp., 1954; $12.00 or 75/.

This book, by the well-known Finnish geochemist, formerly at the University of Chicago, is a very remarkable production. 'Isotope Geology,' a convenient term coined by the author, means the use of the stable and unstable isotopes of the chemical elements, and changes in their ratios for any given element, as a tool in the investigation of geologic phenomena.

The word 'isotope' was devised by Soddy at the turn of the century to characterize chemical elements that differed in mass but not in chemical properties, one of the first such being Io and Th. Work on isotopes, first confined to the radioactive elements was transferred to the stable ones by Aston. Variation in the natural proportions of stable isotopes was first suggested by Briscoe and Robinson, and proven by Nier. In recent years various studies of isotopes, including the geologic and geophysical applications thereof have increased enormously, and the time for a book such as this is ripe. The author has made many valuable contributions to the field, and is well qualified to write the definitive treatise on this interesting and worthwhile subject. He has done a very fine job.

The book is divided into two parts. Part I consists of a well-written, concise, and adequately full account of those parts of modern nuclear physics needed to understand the meaning of the term isotope; the methods of measuring isotope ratios in the various elements; natural radioactivity, its properties, measurement, and geologic applications; and allied topics needed to understand the specific studies in Part II. The treatment is clear and not too mathematical for the field geologist. In a few places the going is a little difficult, but only where modern views and theory are still not clearly worked out. There are only two statements in this part with which the reviewer does not completely agree: on page 74 the radioactivity of Bi needs further confirmation, and on page 103 the absence of a quantitative importance for (n, p) reactions is an understatement. A few references do not appear in the Bibliography, and the Göteborg work on ocean cores is omitted here. This section will interest the Earth scientist more than the physicist.

Part II considers the isotope ratios (where more than one isotope to an element), their variation (or lack of it) in nature, and the geologic and geophysical implications thereof for each element in turn, starting with hydrogen and ending with californium.

Numerous tabular data are very well arranged. The discussion of 'age effects' -- the reviewer's own field -- is better done than the reviewer could do it. Errors are virtually non-existent. In Table 17.2, page 236, the ThO_2 content of the pitchblendes was less than 0.01 pct. In Chapter 19, 'fission' Ne is not mentioned. In Chapter 22 the work of Kulp and others on S isotope variations is not noted, but apparently they had not formally published when the book was written. The reviewer feels that the discussion on iron isotopes in Chapter 30, pages 318-319 goes a little beyond existing evidence. In Chapter 33, page 321, the early work of Baxter and Thomas on Cu from horseshoe crab 'juice' is omitted. These are minor imperfections in an impressively complete and accurate piece of work. This Part II should be in the hands of nearly all physicists, as well as in those of all workers in the Earth sciences.

The bibliography, placed at the end of the book, omits no research papers as far as the reviewer can tell -- and includes many that he had missed. A few items mentioned in the text that are not connected with specific points are missing; for example, references to A. S. Russell and to L. A. Turner on page 79. The indices appear to be complete.

The English usage and literary style of the author are remarkably good. There are only 'micromicro amounts' of his Scandinavian background. The makeup, printing, and binding are excellent. Figure 41.1, referred to on page 335, appears after page 356. One real criticism: 'data' is always used as if it were a feminine singular noun, and not properly as a neuter plural.

'Data are' is correct, 'data is' is wrong. We suggest the Pergamon Press hire a proof-reader with a classical education.

JOHN PUTNAM MARBLE

GOLDSCHMIDT, V. M. (edited by Alex Muir), Geochemistry, Oxford at the Clarendon Press, xi + 730 pp., 1954, $11.05.

V. M. Goldschmidt was one of the most prolific experimentalists in crystal chemistry. Through his interpretations of geologic processes in the framework of crystal chemistry and physical chemistry, he became the foremost leader of the present school of geochemistry. His outstanding contributions helped greatly to spearhead the movement which has caused the widespread application of geochemistry to geology. This book is the record of his work.

The book was in preparation in the closing years of Goldschmidt's life but death prevented him from completing it, and the task of assembling and editing the text fell upon Alexander Muir of the Rothamsted Experimental Station, Harpenden, Herts., England. Muir has been successful in his task despite the unevenness caused by the unifying of a collection of chapters and of translations of previously published articles. The reader should be forewarned that in order to preserve Goldschmidt's treatment of the subject (as it had already been written) some out-dated material is necessarily included.

The text is divided into two parts. The first part (125 pages) is made up of six chapters which deal with the principles of geochemistry and contain Goldschmidt's approach to the problems of geochemistry through crystallochemical concepts.

The second part (576 pages) describes the geochemistry of the individual elements. The abundance and history of the elements are traced from their occurrence in the minerals of the magmatic rocks, and in late stage magmatic products, through the processes of weathering and soil formation. Geochemical data for elements in meteorites, the atmosphere, sea-water, and metamorphic rocks are given when appropriate.

Scientists who have read other texts on geochemistry will want to read this book in order to pursue further the ideas of Goldschmidt mentioned or alluded to by those who quote and use his works. The germs of ideas and applications are interspersed here and there in the text and many of these nebulous suggestions will inspire the receptive reader with the desire to undertake investigations in line with Goldschmidt's thoughts.

The reviewer recommends the work of this distinguished scholar to all who are interested in geochemistry.

GEORGE T. FAUST

LEVORSEN, A. I., Geology of Petroleum, W. H. Freeman and Co., San Francisco, vii + 703 pp., with 327 text figures and 47 tables, 1954, $8.00.

The work of the petroleum geologist has greatly expanded in the last few decades to require a knowledge of the stratigraphy and the means of exploration for the pools remaining to be found, the methods of obtaining and recording geologic data in exploratory and development wells, the character of the reservoirs and the fluids in them, and the economics involved in finding and producing oil from part or all of a pool, field, or province. Because of these many phases of activity in the field of petroleum geology, it is impossible to include in one book a complete discussion of the entire field. The author, who has stated that several books are necessary to cover completely the different types of work for which the petroleum geologist is now responsible, has given a comprehensive discussion of the topics that seemed to require special attention.

This book is a splendid treatment of the geologic occurrence of petroleum and the types and characteristics of the reservoirs in which it is found. The stratigraphic sequence and structure of the rocks in the most important producing fields throughout the world are shown by numerous cross sections and contour maps. Although these areas of production are not discussed geographically, they may be readily referred to by means of the comprehensive index totalling 35 pages. The chapters on reservoir fluids, reservoir mechanics, and economic factors add materially to the value of the book.

It is of particular interest to the reader to have the author's conclusions and the imposing list of references, both general and specific, at the end of each chapter. The book will serve not only as an excellent text for students of petroleum geology but also as a valuable source of reference material for the petroleum geologist.

The drilling rig, derrick, and pump jack are familiar sights to people of the oil and gas producing areas of our country, but many students in petroleum geology have not had the opportunity of seeing an oil field. I believe a few illustrations of these important facets of the petroleum industry in the introduction would be interesting and helpful to those who have not had the fascination of being on rig when the bit was spinning down.

For textbook or reference to problems in petroleum geology, this book can be highly recommended.

GEORGE V. COHEE

VISHER, STEPHEN S., Climatic Atlas of the United States, Harvard University Press, Cambridge, Mass., xii + 401 pp., 1031 figures, 1954.

This impressive collection of climatic charts, all under one cover, presents a general United States survey of many aspects of temperature, wind, pressure, storms, sunshine, humidity, evaporation, precipitation, and climatic effects, regions, and changes. The atlas is not a suitable source of exact numerical values because details have been omitted for the sake of clarity according to the author. For maps of larger scale, with more detail and greater accuracy, Visher refers to Climate and Man, Yearbook of Agriculture, 1941, Atlas of American Agriculture (1936) (both published by the U. S. Department of Agriculture), and many other fine references.

The charts in Visher's atlas would be more useful if the legend for each chart stated the period of years covered by the data. Also definitions are needed for the following terms used in the legends: winter, summer, spring and fall quarters, cold and hot waves, frequent, rare, sizeable area, excessive rains, brief and prolonged heavy rains, dry, wet, humid, superhumid, normal relative variability, and other criteria. The smoothing of some lines and the omission of other lines cause inaccuracies which are greatest in coastal areas, where the lines are drawn nearly perpendicular to the coast and ended instead of being crowded together and extended nearly parallel to the coast. For example, errors up to 10° or even 20° F appear at San Francisco on the charts of mean, maximum, and minimum daily temperatures for summer weeks. Normal conditions may be confused with actual conditions or vice versa because of misleading labels on some charts or legends. In several instances, the charts are paired with the wrong legends, and the chapter and page headings for dry and wet periods are reversed.

The source for each chart is conveniently listed at the end of the atlas.

EDWARD M. BROOKS

Abstracts of the Pacific Southwest Regional Meeting, University of California, Berkeley, California, February 4-5, 1955

The following are abstracts of the papers presented at the meeting held by the Pacific Southwest Regional Committee at Berkeley, California, February 4-5, 1955. These relate primarily to Meteorology, Oceanography, and Hydrology, and are listed in order by the last name of the first author.

Henry W. Anderson (California Forest and Range Experiment Station, Berkeley, Calif.) Forest Effects on Snowpack Accumulation and Melt, Central Sierra Snow Laboratory--Snowpack accumulation and melt at individual snow measurement points within snow courses were related to the forest shade, and to the height of the trees and distance of the trees from the snow measurement point. Accumulation of snow as of April 1 of each year and melt per unit of degree-days above 35°F were studied. For trees to the south of the snow measurement point the amount of shade was expressed quantitatively as the duration of shading between April 1 and June 15, multiplied by the amount of solar energy which would have impinged on the snow surface in the absence of shading. For trees to the north of the snow measurement point, the forest cover was expressed by the average ratio of height to distance of the trees. Five snow measurement points in each of five snow courses for three years of record were analyzed by the method of covariance. The results were interpreted in terms of forest management for maximum accumulation or minimum melt rate of the snowpack.

Harry F. Blaney (Agricultural Research Service, U. S. Department of Agriculture, Los Angeles, Calif.) Report on the Tenth Assembly of the International Union of Geodesy and Geophysics in Rome, Italy--Delegates from some 45 countries attended the Tenth General Assembly of the International Union of Geodesy and Geophysics in Rome, Italy, September 14-25, 1954. The program was sponsored by the constituent International Associations of Geodesy, Seismology, Meteorology, Terrestrial Magnetism and Electricity, Oceanography, Volcanology, and Hydrology. About 1500 people attended the convention including 165 from the United States. The next Assembly will be held in Buenos Aires, Argentina, in 1957. Summaries of 200 papers were given to each delegate attending the sessions of the Association Internationale d'Hydrologie. These papers included the subjects of precipitation, run-off, evaporation, consumptive use, snow, recharge of ground-water fluctuations, and quality of water and erosion. Lack of time prevented presentation of many of these papers. However, many of the papers will be published in the proceedings of the Assembly.

C. L. Bretschneider (Dept. of Oceanography, Texas A. and M. College, College Station, Texas) Generation of Wind Waves Over a Continental Shelf--The combined effects of generation of wind waves by wind blowing over water and dissipation of wave energy brought about by bottom friction leads to a method of predicting wind waves in shallow water. This is done by numerical integration, wherein wave energy is added due to wind stress and subtracted due to bottom friction. Computations yield a set of dimensionless parameters gT/U and gH/U^2 versus gF/U^2 and gd/U^2 for each type of bottom. In the above parameters, g = acceleration of gravity, T = significant wave period, H = significant wave height, F = fetch length, d = depth of water, and U = wind speed. Wave data from Lake Okeechobee, Gulf of Mexico, and wave tank studies show good agreement with the values computed by numerical procedure.

Edward A. Colman (California Forest and Range Experiment Station, Berkeley, Calif.) Proposed Research in Snow-Pack Management in California--Observation and research suggest that accumulation and melt of snow, and evaporative water losses are subject to some control by man. Control can be achieved by opening dense forests in certain patterns or by creating wind-breaks. Snow-pack management, thus achieved, should improve water supplies by reducing water waste in snow-melt floods, prolonging the snow-melt season, and increasing the usable water yield of snow-pack lands. Research in snow-pack management is needed in California; results of research done elsewhere may not apply here because of differences in weather and forest conditions. Research proposed here includes investigation of methods for controlling snow accumulation and melt and evaporative losses under various topographic and forest conditions, followed by pilot testing of promising methods of land treatment on calibrated watersheds. Logging is moving up into California's snow-pack lands. The proposed research will show how these forest lands can be managed for improved water yield as well as timber production.

Robert E. Glover (U. S. Bureau of Reclamation, Denver, Colo.) A New Method for Predicting Transient States of Salinity Intrusion into the Sacramento-San Joaquin Delta--The mechanism by which the tidal changes propagate salinity into the Delta channels and the manner in which this propagation is opposed by the fresh water stream flows are expressed in mathematical form. Solutions of the basic differential equation are given which are suitable for computation of salinity changes and a method of computation is described. As an example of the use of these methods they are applied to the historical records to determine a depletion curve for the Delta by using the observed salinities as an indicator and finding the flows out of the Delta which were necessary to hold the salinities to the observed amounts. While the primary usefulness of this depletion curve is to form a basis for further estimates of ocean salinity encroachment, it is compared to use curves derived from independent sources.

W. J. Kaufman and G. T. Orlob (Division of Civil Engineering and Irrigation, University of California, Berkeley, Calif.) An Evaluation of Ground-Water Tracers--Organic, inorganic, and radioactive tracers have been studied with lysimeter columns containing three representative California soils. The modification of the tracer break-through curve by soil adsorption has indicated an inherent weakness in certain of the radioactive isotopes when used as water tracers. Field studies of radioiodine have been carried out using a recharge well and a system of radial observation wells.

A. D. K. Laird (Div. of Mechanical Engineering, University of California, Berkeley, Calif.) A Model Study of Wave Action on a Cylindrical Island--(Full paper with abstract appears in this number of the Transactions, on pp. 279-285.)

A. R. Leonard and Seymour Mack (U. S. Geological Survey, Sacramento, Calif.) Notes on the Relation of Geology to Water Quality in Scott Valley and the Smith River Plain, California--Ground water investigations by the U. S. Geological Survey indicate that the quality of ground and surface waters in Scott Valley and the Smith River plain can be correlated with the composition of bedrock in those areas. In both areas streams and ground water from serpentine areas have magnesium as the dominant cation. In Scott Valley, waters draining from plagioclase-bearing crystalline rocks are soft and have a high percentage of sodium; waters from limestone terrain are hard and have calcium as the dominant cation; and waters from areas of pyrite-bearing greenstone are high in sulfate.

Gordon L. Long (Division of Water Resources, State of California, Sacramento, Calif.) Geophysical Considerations of Salinity Control Barriers in San Francisco Bay--Geophysically speaking, the San Francisco Bay system is not the series of connected water bodies commonly conceived by laymen. It is a continuous tidal estuary. The regimen involves a delicately balanced trend established by complex interrelation of geophysical elements. Principal and primary elements are: (1) Tides; (2) Stream flow; and (3) Sediments.

The geophysical regimen of the San Francisco Bay system is sensitive to changes in any of the composing element or their correlation or both whether caused by nature or man. A salinity control barrier within the Bay system would greatly alter the natural association of geophysical elements. Proper consideration of such a work must attempt evaluation of the probable resulting impact, not only as it might effect the established community but also to determine the functional feasibility of a barrier itself.

The California Water Project Authority is making an investigation of the feasibility and economic value of salinity control barriers in San Francisco Bay. A report will be presented to the Legislature in March 1955. Engineering studies for the investigation were delegated to the State Department of Public Works, Division of Water Resources, under direction of the State Engineer.

John F. Mann, Jr. (Geology Department, University of Southern California, Los Angeles, Calif.) Spring Sapping in Hueneme and Mugu Submarine Canyons--In 1937 Douglas Johnson suggested spring sapping as an important process in the formation of submarine canyons. In a series of papers in 1938 and 1939 he expounded on the hypothesis, presenting evidence to indicate that such a process is or was possible on the continental slope off the east coast of the United States. Unfortunately, he was not able to refer to any specific submarine canyon where there was good evidence that such a process had operated. Near Ventura, California, is to be found strong evidence of the spring sapping idea. Here, confined Recent and Pleistocene sands crop out within Hueneme and Mugu submarine canyons. Artesian water levels in those aquifers close to the shoreline indicate that fresh water has escaped at the submarine outcrops in the canyons. Futhermore, at times of lowered sea levels fresh water must have been escaping at a greater rate than now.

M. Manohar (Wave Research Laboratory, University of California, Berkeley, Calif.) Mechanics of Bottom Sediment Motion Due to Wave Action--The effect of the action of surface waves on the movement of bottom sediment is analysed experimentally and analytically. It is found that due to surface wave action there are initial and general sediment motions, initiation, various stages of development and complete disappearance of sediment undulations or ripples. Depending upon the flow conditions in the boundary layer that is developed at the bottom due to effects of viscosity of fluid, it is found that for very small grain sizes, initial and general motions are due to laminar shear while for large sizes, these motions are due to lift forces in turbulent flow. Ripples, in general, are formed in turbulent flow. Sediment motions in turbulent flow and the various stages of development of the ripples are found to be functions of a dimensionless parameter representing intensity of flow on the particles.

Dean C. Muckel and Harry F. Blaney (Agricultural Research Service, U. S. Department of Agriculture, Berkeley and Los Angeles, Calif.) Evaporation and Evapotranspiration Investigations In the San Francisco Bay Area--During 1953-54, studies were made to determine probable evaporation and evapotranspiration losses that would occur from fresh-water pools if saltwater barriers were constructed across San Francisco Bay. Available measurements of evaporation and consumptive use of water were compiled. New stations were established in areas not covered by existing stations and measurements made of evaporation, temperature, humidity, wind movement, and precipitation. Evaporation and consumptive use data were correlated with climatological records and estimates were made of annual and monthly rates of evaporation from lake surface and consumptive use by march vegetation for the 1921-1952 period and for the five critical years, 1923, 1924, 1930, 1931, and 1951.

Walter J. Parsons (Corps of Engineers, U. S. Army, Sacramento, Calif.) The Menace of Snow-Melt Floods--Winter snow packs in the mountains are normally beneficial, but may constitute a flood threat to valley areas. There are generally three ways in which the snow pack can cause floods; (1) by augmenting a rain flood (a shallow pack is most dangerous in this way); (2) by melting

rapidly during an hot spell (a moderately deep pack is most dangerous for this type); and (3) by producing excessive volumes of runoff which exceed the capacity of storage reservoirs. The first two types cannot be predicted long in advance and must be fought with facilities on hand. The last type can usually be predicted months in advance so that all available means can be used to minimize its damage. Each type of flood is analyzed for its causative elements, and means of forecasting these elements are discussed.

J. F. Poland and G. H. Davis (U. S. Geological Survey, Sacramento, Calif.) Subsidence of Land Surface in the Delano and Mendota-Huron Areas, San Joaquin Valley, California--Releveling of benchmarks in 1953 and 1954 by the Coast and Geodetic Survey indicates that subsidence of land surface has now exceeded ten feet in two areas of the San Joaquin Valley. In the Delano area of Tulare County, subsidence which was as much as five feet in 1940 now has about doubled. The maximum rate of subsidence in recent years has been about 0.5 foot a year. In the Mendota-Huron area of western Fresno County, major subsidence extends from Ora Loma on the north beyond Huron on the South, a distance of 70 miles or more. The maximum rate there approaches one foot a year. Plots of subsidence against decline in artesian pressure suggest that pressure decline is a major cause of the subsidence. Compaction of the soil after irrigation is known to have caused substantial local subsidence in the Mendota-Huron area, and tectonic adjustement also may have contributed in the subsidence.

G. C. Ralls, Jr. (Wave Research Laboratory, University of California, Berkeley, Calif.) A Ripple Tank Study of Wind Generated Short-Crested Waves--Some fundamental characteristics of short-crested waves have been studied. As well as indicating results of the study, a detailed discussion of the experimental apparatus, its design, calibration, and use is included. Much of the report is qualitative in nature due to lack of an adequate theory. The quantitative portion of the paper is based primarily on Fuch's Theory for predicting the velocity of short-crested waves. Possible methods of analysing short-crested patterns to obtain wave parameters are discussed. Some changes in future experimental apparatus to enable a more extensive study are included. The results presented are based in a three-dimensional study in a ripple tank 0.5 foot deep by four feet wide by 20 feet long.

Eugene P. Richey (Department of Civil Engineering, University of Washington, Seattle, Wash.) The Mechanics of Overland Flow--The differential equation for the surface profile in overland flow is derived for steady-state laminar flow and then extended into the turbulent range. The exact solutions obtained by numerical integration are used to measure the significance of the errors introduced by the assumptions needed to develop simplified solutions. The physical meaning of certain runoff coefficients is shown by an analysis of the basic equation and its solutions.

Osvald Sibul (Wave Research Laboratory, University of California, Berkeley, Calif.) Laboratory Studies of Wind Tides in Shallow Water--Wind tides and wave conditions in shallow water were studied in a laboratory channel. The experiments were conducted with smooth and rough bottom conditions and with strips of cheese cloth in the channel to simulate the roughness effects of vegetation in nature. The results indicate a rapidly increasing set-up when the still-water depth decreases beyond a certain limit. There were no indications that the bottom roughness effects the set-up for relatively deep water. In very shallow water, however, the rougher bottom conditions result in higher set-ups. The trend is especially definite for higher wind velocities. For the shallowest still-water depth (0.05 foot) used in this experiment, set-up was approximately ten per cent higher for the rough bottom and approximately 20 per cent higher when strips of cheese cloth were used in the channel to simulate the roughness effect of vegetation.

John A. Stirton (Corps of Engineers, U. S. Army, San Francisco, Calif.) A Proposed Model Study of San Francisco Bay--Some hydraulic and related problems connected with shoaling of navigation channels in San Francisco Bay under existing conditions and of problems related to various proposals for both construction of barrier-type structures in, and reclamation of portions of, the Bay are reviewed. Prior model studies of problem areas in the San Francisco Bay system are listed. A comprehensive hydraulic model to be used in an attempt to obtain a solution of the problems is described. An outline of the prototype data required for construction, verification and operation of the model is given. Basic data suitable for use in model operation and contained in reports of previous investigations of salt-water barriers are summarized and additional prototype data required for model verification are discussed.

Fred A. Strauss (California Division of Water Resources, Sacramento, Calif.) Snow as a Source of Water Supply in California--Practically no rain occurs in California from the beginning of June until the end of September, all water used during that period must be supplied from the pre-

cipitation of the preceding winter which has been held over by natural means or artificial control. This paper evaluates California's mountain snowpack, one of nature's storage facilities, which makes possible the year-round supply of water so necessary to that State's economy.

Harold C. Troxell (U. S. Geological Survey, Los Angeles, Calif.) Hydrology of the San Bernardino and Eastern San Gabriel Mountains, California--Description of a new kind of atlas recently published by the Geological Survey; see Bibliography of Hydrology, U. S. Geological Survey.

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NOTES AND PERSONALIA

NOTES

Corrigendum--In December issue of the Transactions, page 1014, the list of the members of the Committee on Tides of the Association of Oceanography is given. We have received word that A. Gougenheim (France) has replaced J. B. Schijf (The Netherlands) as Secretary, though Schijf remains on the Committee. K. Hidaka (Japan) has replaced K. Terada (Japan).

Meeting of the Mixed Commission on the Ionosphere to be held in London, August 22-24, 1955--A Symposium under the general title of Solar Eclipses and the Ionosphere will be held under the auspices of the Mixed Commission on the Ionosphere of the International Council of Scientific Unions in Burlington House, London, August 22-24, 1955. The topics under the Symposium are: Ionospheric and other geophysical eclipse phenomena, Recent ionospheric eclipse results, Ionospheric processes--ion production and recombination, Sources of ionizing radiation, and Radio astronomical eclipse observations. Persons desiring further information should write to Dr. W. J. G. Beynon, Secretary of the Mixed Commission on the Ionosphere, Department of Physics, University College, Swansea, England.

Lectureship and fellowship available at the University of Toronto--The Department of Physics of the University of Toronto has a vacancy for a lecturer in exploration geophysics for one acquainted with gravimetric, electromagnetic, and seismic instruments, with the appointment to be effective September 1, 1955. A Research Fellowship given jointly by the University, California Standard Company, and the California Research Corporation is available for someone with a baccalaureate degree who is interested in continuing study in exploration geophysics or the physics of the Earth. Application should be made to W.H. Watson, McLennan Laboratory, University of Toronto, Toronto 5, Canada.

Special short courses at Massachusetts Institute of Technology--Massachusetts Institute of Technology announces the arranging of two short courses in meteorology. The first of these will be regarding weather radar to be held June 14-24, inclusive, and the second in numerical weather prediction to be held June 27-July 8, inclusive. Details may be secured from the Office of Summer Sessions, Room 7-103, M.I.T., Cambridge 39, Massachusetts.

Special course in Photogrammetry--The Institut Geographique National announces that it will offer courses in Aerial Photogrammetry, June 27-August 6, 1955. Details may be secured by writing to L. Hurault, Le Directeur de l'Institut Geographique National, Ecole Nationale des Sciences Geographiques, 2, Avenue Pasteur, Saint-Mande (Seine), France.

Sixth Alaska Science Conference to be held June 1-4, 1955--The sixth Alaska Science Conference, under the auspices of the Alaska Division of the American Association for the Advancement of Science, is to be held at College, Alaska, June 1-4, 1955. Quite a full spectrum of the sciences will present programs. Details may be secured by writing to A. S. Buswell, Secretary, Alaska Division, AAAS, Box B, College, Alaska.

Fellowship awards of the National Science Foundation--The National Science Foundation has announced the awarding of 715 pre-doctoral fellowships and 70 post-doctoral fellowships, these from 2931 applicants. Honorable mention was accorded to 1409 additional applicants. Among those awarded were 151 in the field of physics, 107 in engineering sciences, 30 in the Earth sciences, and 14 in agriculture. Details concerning the awards with the names of the recipients may be secured through the National Science Foundation, Washington 25, D. C.

Grants of the National Science Foundation--The National Science Foundation has recently announced 120 grants in support of science, quite a number of which involve various aspects of the Earth sciences. Among these are: University of Chicago (Hans Ramberg), Thermodynamic study of minerals, three years, $27,000; Columbia University (J. Laurence Kulp), Carbon 14 dating of archeological and anthropological specimens, one year, $10,000; Dartmouth College (J. B. Lyons), Systematic compositional variation in metamorphic minerals, two years, $7,200; Franklin and Marshall College (Richard M. Foose), Structural patterns around the perimeter of the Beartooth Block in southwestern Montana, two years, $10,000; Johns Hopkins University (R. B. Montgomery), Analysis of serial oceanographic observations, two years, $9,000; Lehigh University (H. R. Gault), Studies of carbonate rocks, two years, $6,800; Pennsylvania State University (Charles L. Hosler), Aggregation of ice crystals to form snow, two years, $10,000; Saint Louis University (Ross R. Heinrich), Atmospheric micro-oscillations and short-period microseisms, three years, $36,000; Texas A and M Research Foundation (Donald W. Wood), Calcium carbonate solubility equilibrium in sea water, three years, $20,000.

Progress on plans for the International Geophysical Year, United States participation--The icebreaker USS ATKA, which left for Boston in early December for Antarctic on an exploratory and preparatory mission in connection with the work of the International Geophysical Year, has now returned from a successful voyage. The expedition was engaged in reconnaissance work in the locating of bases of operation for the United States part of this international effort.

Recently, meetings were held in Washington by the U. S. National Committee of IGY, and in

connection with these one full day was devoted to open discussion to bring the United States scientific public up to date with regard to the plans. Details may be learned by addressing the U. S. National Committee for IGY, National Research Council, Washington, D. C.

Eighteenth International Geographical Congress--As noted in the December issue of the Transactions, page 1006, this Congress is to be held in Rio de Janeiro, August 9-18, 1956. Further word from Executive Secretary Sternberg relative to the Congress transmits more detailed plans with a tentative agenda, including the plans for excursions. Persons interested in securing a copy of this material should address their request to Hilgard O'Reilly Sternberg, Centro de Pesquisas de Geografia do Brasil, Av. Presidente Antonio Carlos, 40-9° andar, Rio de Janeiro, Brazil.

Improved New Zealand seismograph--A new electronic strong-motion seismograph has been developed by New Zealand scientists, this recording Earth tremors directly on non-photographic paper and thus making the record immediately available for use.

New research and development corporation--The Capitol Research and Development Corporation has been organized to undertake research work in geophysics and geography. Specialists and inventors working with the corporation will have the advantage of a unique profit-sharing plan. Temporary quarters have been established at 4120 34th Street North, Arlington, Virginia. Leo Alpert is the President of the Corporation.

PERSONALIA

Talbert Abrams, President of Abrams Aerial Survey and Abrams Instrument Corporations of Lansing, Michigan, has been given the Michigan State College Centennial Award in recognition of distinguished services that have contributed to the benefit of mankind.

Charles F. Brooks, Director of the Blue Hill Observatory of Harvard University, who organized the American Meteorological Society in 1919 and has served as its Secretary until very recently, was recently honored by the Society for his many years of service to the American Meteorological Society.

Felix Chayes, petrologist of the Geophysical Laboratory of the Carnegie Institution of Washington and Secretary of the Section of Volcanology, Geochemistry, and Petrology, AGU, served as Visiting Professor of Petrology at California Institute of Technology during the winter term.

Rhodes W. Fairbridge of the University of Western Australia, and during 1953 visiting professor at the University of Illinois, has been appointed Professor of Geology at Columbia University.

George H. Hickox of the National Science Foundation has been elected an officer of the Research Branch of the National Association of Land Grant Colleges.

Serge A. Korff of New York University has been elected President of the Explorers' Club.

Walter C. Lowdermilk, Consultant to the United Nations on economic development and Past President of AGU, is now in Israel where he is serving as the Head of the new Department of Agricultural Engineering in the Israel Institute of Technology and Consultant to the Government of Israel on soil and water conservation problems.

Jerome Namais, Chief of the Extended Forecast Section of the U. S. Weather Bureau and Vice President of the Section of Meteorology, AGU, has been given the Award for Extraordinary Scientific Accomplishment by the American Meteorological Society.

Frank Press has resigned his position as Associate Professor of Geophysics at Columbia University to take up duties in mid-September, 1955, as Professor of Geophysics in the Division of Geological Sciences at California Institute of Technology

Howard S. Rappleye of the U. S.. Coast and Geodetic Survey, retired, has been elected Treasurer of the Washington Academy of Sciences.

Everett W. Rowland has resigned from his position with the U. S. Bureau of Reclamation and taken up duties with Knappen-Tippetts-Abbett-McCarthy, Engineers, with headquarters in New York.

William W. Rubey, Geologist of the U. S. Geological Survey, is now on a six-month appointment as Visiting Professor of Geology at California Institute of Technology.

Athelstan F. Spilhaus, Dean of the Institute of Technology at the University of Minnesota, who served as U. S. Delegate at the Eighth General Conference of UNESCO at Montevideo, has been elected to serve on the Executive Board of UNESCO through 1956.

Walter D. Sutcliffe has retired from his position as Geodetic Engineer and Chief of the Field Records Branch, Division of Geodesy of the U. S. Coast and Geodetic Survey.

F. J. Veihmeyer, who has recently retired as Professor of Irrigation at the University of California at Davis, and who served from 1950 to 1953 as President of the Section of Hydrology, AGU, has accepted assignment as a Consultant to the Chilean Government and will conduct seminars and classes relating to irrigation science in connection with the work of the Ministry of Agriculture of Chile.

John C. Whitaker has resigned from his position with the Standard Oil Company of California to accept a position as geologist with Lundberg Explorations, Ltd., with headquarters in Toronto, Canada. The company is active in the field of airborne radioactive and electromagnetic surveys.

Robert Balk of the Bureau of Mines and Mineral Resources, New Mexico Institute of Mining and Technology, was killed in an airplane accident near Albuquerque, New Mexico, on February 19, 1955, at the age of 55. He was born at Reval, Estonia. He took his doctorate from the University of Breslau in 1924, shortly migrating to the United States. Upon his arrival, he entered into work with the New York Geological Survey, and in the fall of 1925 served as Assistant Professor of Geology at Hunter College, where he remained until 1935. From 1935 to 1947, he was Professor of Geology at Mt. Holyoke College. He took up duties at the University of Chicago in 1947, continuing until 1952, when he joined the staff of the New Mexico Bureau of Mines and Mineral Resources. In December 1954, he completed a term as Visiting Professor of Structural Geology at California Institute of Technology. He became a citizen of the United States in 1932. He was Vice President of the Section of Tectonophysics from 1947 to 1950, and President of the Section from 1950 to 1953. He had been a member of AGU since 1935.

Joseph Burton Kincer, Chief of the Division of Climate and Crop Weather of the U. S. Weather Bureau, retired, died in Washington, D. C., December 13, 1954, at the age of 80. He was born at Wytheville, Virginia, and, after attending private schools and devoting a number of years to teaching, he entered the service of the Weather Bureau in 1905. He became a recognized world authority in climatology through his extensive writings and other work. He retired in 1944, but maintained his interests in meteorology in various ways, and served as Editor in Meteorology for AGU in 1945 and 1946. He became a member of AGU in 1930.

John R. Kinney, Senior Civil Engineer of the Department of Public Works in Kansas City, Mo., died December 28, 1954, at the age of 44. He was born at Davenport, Iowa, and took his baccalaureate degree from Iowa State College in 1935. The first years of his professional career were devoted to work with the Corps of Engineers on the Missisippi River, and later with Omaha and Kansas City Districts. He devoted about a year in 1946 and 1947 to work with Black and Veatch, Consulting Engineers of Kansas City, and entered the service of the Kansas City Department of Public Works in 1947, devoting his energies to the design of sewerage and flood-control facilities. He had been a member of AGU since 1945.

Oliver Clarence Lester, Emeritus Dean of the Graduate School and Professor of Physics, University of Colorado, died September 28, 1951, at the age of 77. He was born in Morris County, Kansas, and took his baccalaureate degree from Central College, Missouri, in 1897, and his master's degree from the same school in 1898. He took a master's degree from Yale in 1902 and his doctorate in 1904. He became an instructor in physics at Yale in 1904, where he remained until 1907. In that year, he took up duties as Professor of Physics at the University of Colorado, serving also as Dean of the Graduate School from 1919 and as Acting President during several periods. He became Emeritus Professor, Dean, and Vice President in 1942, and was subsequently Professor of Physics at the University of Indiana and at the University of Colorado. He has served as consultant and in various capacities for various organizations during his long career. He became a member of AGU in 1930.

UNION, SECTION, AND COMMITTEE ACTIVITIES

REPORT OF THE COMMITTEE OF TELLERS ON THE RECENT BALLOT ON THE CHANGES IN STATUTES AND BY-LAWS

Harry S. Ladd, Chairman

Gordon Lill
Kenneth E. Lohman
John Putnam Marble
H. Kirk Stephenson
Joel Swartz

Our Committee of Tellers met at 1530 P Street on February 23 and tabulated the ballots of the recent vote on changes in the Statutes and By-Laws. Before opening and counting the main mass of ballots we considered several odd lots, as follows:

(a) 2 ballots without external identification; these were opened, identified as bona fide ballots, and counted.
(b) 9 ballots mailed and received late; the Committee voted unanimously to count these.
(c) 6 ballots from members who were six months or more in arrears in dues were not counted.
(d) 30 ballots from members not citizens of the United States. These were not counted.
(e) 2 ballots from members who also submitted resignations. These were counted.

A total of 1651 members took advantage of the short cut offered by the topmost box on the ballot, thus giving blanket approval for the 6 items presented.

The voting on individual items was as follows:

	Yes	No
Item 1--To change the name of the Section of Volcanology to the Section of Volcanology, Geochemistry, and Petrology	1880	41
Item 2--To provide for a student grade of membership	1917	46
Item 3--To provide for a Committee on International Participation	1914	41
Item 4--To recognize the organizational changes in the National Research Council and the National Academy of Sciences	1926	15
Item 5--To provide greater flexibility in the operation of the Union	1790	148
Item 6--To provide for greater flexibility on the part of the Executive Committee in meeting the fiscal problems of the Union	1807	145

Total number of ballots received		1999
Rejected ballots		
From delinquent members	6	
From non-citizens	30	36
Qualified ballots tabulated		1963

Nine ballots were received after the Committee completed its tabulation. These were not counted.

CONTINUATION OF THE REPORT OF THE COMMITTEE ON STATUTES AND BY-LAWS

K. Hilding Beij, Chairman

Ralph R. Bodle
John A. Fleming

(Note: In the Report of this Committee, reported in the Transactions of February, 1955, pages 165-166, Items (1) and (2) of the Report were not included, pending clarification of a few details. These seem now to have been clarified, and the balance of the Report, as approved, with the Statutes and By-Laws of the newly organized Pacific Northwest Regional Branch and the Constitution and By-Laws of the Mid-Pacific Regional Branch, with appropriate changes in the Statutes and By-Laws of the Pacific Southwest Region, is published below. Since the filing of this Report, the Committee has been reorganized, with R. R. Bodle as Chairman, K. Hilding Beij remaining as a member.)

(1) It is recommended that the proposed Statutes and By-Laws for the Pacific Northwest Region (see Appendix I) be approved.

(2) It is recommended that the Constitution and By-Laws of the Geophysical Society of Hawaii (see Appendix II) be approved, subject to the following. Up to the present the Society has been organized as part of the Pacific Southwest Region. It is proposed that the Society be made an independent branch of the Union to be known as the Mid-Pacific Regional Branch. If this proposal is adopted, the following amendments to Article 3 of its Constitution are recommended (these changes have now been approved by the Region):

(a) In paragraph (1) delete the words "and the Union's Pacific Southwest Region."

(b) In paragraph (3) change the last word to the plural form, i.e., "organizations."

(c) In paragraph (4) delete the words "and the Chairman of the Pacific Southwest Regional Committee of the A.G.U."

Also the following amendment to the By-Laws for the Pacific Southwest Region [Trans. AGU, v. 33, page 629, Aug., 1952] is recommended (this change has now been approved by the Region):

In paragraph (1) delete the words "the Territory of Hawaii, and all other territories, possessions, dependencies, or mandates of the United States in the Pacific Ocean south of the 40th parallel."

APPENDIX I--STATUTES AND BY-LAWS OF THE PACIFIC NORTHWEST REGIONAL BRANCH, AMERICAN GEOPHYSICAL UNION

STATUTES

Article 1: Name, Location, and Objectives--(a) The name of this organization shall be the Pacific Northwest Regional Branch of the American Geophysical Union.

(b) This Branch shall include Washington, Oregon, Idaho, Montana, Wyoming, and Alaska.

(c) The objectives of this Branch shall be to promote the aims and activities of the American Geophysical Union within its area of jurisdiction.

Article 2: Membership--This Branch shall be constituted of all members of the American Geophysical Union, in any grade and in all Sections, who reside within the area of this Region and adjacent Canadian Provinces. Should any member of this Branch cease to be a member of the American Geophysical Union he shall also cease at the same time to be a member of this Branch. Inactive members of the American Geophysical Union shall also be inactive members of this Branch.

Article 3: Finances--To defray authorized expenses incurred by this Branch, a registration fee for each meeting, fixed in amount by the Regional Committee, may be charged each registrant.

Article 4: Administration and Officers--(a) The activities of this Branch shall be directed by a Regional Committee, which shall be composed of at least one but not more than three elected representatives from each Section taking part in the activity of this Branch, and not more than nine members in all. The apportioning of these members among the Sections shall be recommended by the Regional Committee to the Sections at least ten weeks before elections, and shall be subject to ratification by these Sections not later than four weeks before elections. Lack of reply from any Section shall be taken as approval of the recommendation. Any one individual shall not represent more than one Section on the Regional Committee.

(b) The term of the Regional Committee and of each of its members shall be for three years and shall begin on July the first at the beginning of each triennium, which shall be identical with the triennium years of the American Geophysical Union. In the case that one or more of its memberships is vacated, the Regional Committee shall select a new representative from the same Section as that represented by each vacancy, this selection to be made before the next annual meeting of the Branch.

(c) The Regional Committee shall select annually a Regional Chairman and a Regional Secretary-Treasurer, who shall not be the same individual. The terms of these officers shall be for one year, beginning on July first of each year. In the case that either or both of these offices is vacated, the vacancy shall be filled by action of the Regional Committee as soon as any vacancies in its membership have been filled, and not later than ten weeks following the creation of the vacancy in office. The Secretary-Treasurer shall be acting Chairman in case the office of Chairman is vacated, until a new Chairman has been selected. An incumbent Chairman shall act in that capacity until new officers have been selected, but it shall be his duty to see that new officers are selected not later than August fifteenth of each year.

(d) The immediate past-Chairman of the Regional Committee shall be an ex-officio member of the Regional Committee for the next succeeding three-year term.

Article 5: Meetings--(a) There shall be an annual meeting of this Branch at a time and place set by the Regional Committee, unless all active Sections decline to participate.

(b) Special meetings of this Branch may be held upon the request of any active Section, or at the discretion of the Regional Committee.

(c) All meetings, any expenses of which are borne by the American Geophysical Union, are subject to approval by the Executive Committee of the Union.

Article 6: Amendments--Any proposed amendment to these Statutes shall be voted on by letter ballot addressed to all active members of the Branch, and shall become effective upon an affirmative vote of not less than two-thirds of the members voting, and upon approval by the Executive Committee of the American Geophysical Union.

Article 7: By-Laws--This Branch may adopt By-Laws consistent with these Statutes for the guidance of the Regional Committee and of members.

BY-LAWS

Article 1: Elections--(a) Elections for membership on the Regional Committee shall be held by mail ballot concurrently with National elections of the American Geophysical Union, at the end of each triennium. That individual gaining a plurality of votes for a given position will be considered elected.

(b) The Secretary-Treasurer of the Regional Committee shall be responsible for the mailing and counting of ballots, and shall promptly report the results to the Sections and to those elected.

(c) Further regulations necessary for the proper and efficient handling of elections may be made by the Regional Committee at its discretion.

(d) The manner of selecting the officers of the Regional Committee shall be at the discretion of that Committee. Each active Section will be notified promptly regarding the results of such selection. The Secretary-Treasurer shall notify the Executive Committee of the American Geophysical Union promptly regarding any changes in officers or membership of the Regional Committee.

Article 2: Quorum--Those present at a Regional meeting shall constitute a quorum.

Article 3: Dues--There shall be no dues for this Branch.

Article 4: Meetings--(a) The Regional Committee may meet at its discretion to transact business relating to this Branch.

(b) The Secretary-Treasurer of the Regional Committee shall mail notices of regular or special Regional meetings not later than 14 days prior to such a meeting. These notices shall be sent to each member of this Branch at his last known address. The expense of these notices shall be a legitimate expense of the meeting.

Article 5: Secretary-Treasurer--(a) As soon as possible after June 30 of each year, the Regional Secretary-Treasurer shall submit a brief report of the year's activities to the General Secretary of the American Geophysical Union.

(b) The Secretary-Treasurer shall present a current financial statement to the Regional Committee upon request from that Committee.

(c) The Secretary-Treasurer and one other member of the Regional Committee appointed by the Regional Chairman shall audit the books of each Regional meeting following the closing of those books.

Article 6: Committees--(a) The Regional Committee may appoint such other committees as are appropriate for carrying out the functions of this Branch.

(b) The Regional Committee shall appoint a committee or committees from the membership of appropriate Sections to organize and bring to completion such Regional meetings as may be called by the Regional Committee. These committees will make a final report, including a financial statement when pertinent, to the Regional Committee following the meeting.

(c) At least one year prior to each triennial election, the Regional Committee shall appoint a committee on nominations. The chairman of this committee shall activate it immediately, and by proper canvassing and conscientious deliberation this committee shall determine the best possible candidates for membership on the Regional Committee. The nominating committee shall submit its nominations to the Secretary-Treasurer of the Regional Committee not later than the 15th of March in each election year. A list of these nominees will be mailed with the election ballots. The expense of this mailing shall be considered an expense of the next Regional meeting.

(d) Any locality within the Region where there is a concentration of members may, on the initiative of a number of those local members, organize a local committee similar to the Regional

Committee, with the aid of the Regional Committee. Such local committees will have a degree of autonomy consistent with high scientific endeavor, but shall maintain close contact with the Regional Committee and with the Executive Committee of the American Geophysical Union. The Regional and National organizations should be given prior notice of plans for meetings by the local groups.

(e) If at any time conditions arise such that there is no Regional Committee for this Branch, a Regional meeting may be called on the initiative of a group or ad hoc committee of members of this Branch. A Regional Committee may then be elected by a majority vote of those present at that meeting.

Article 7: Amendments--These By-Laws may be amended by a majority vote of the members in the Region voting, subject to approval by the Executive Committee of the American Geophysical Union.

APPENDIX II--CONSTITUTION AND BY-LAWS OF THE GEOPHYSICAL SOCIETY OF HAWAII

(Mid-Pacific Regional Branch, American Geophysical Union

CONSTITUTION

Article 1: Name--The name of this organization shall be the Geophysical Society of Hawaii.

Article 2: Objects--The objects of the society are to serve as the Mid-Pacific combined Regional Branch of the American Geophysical Union and American Meteorological Society and to assist in carrying out the objects of these national organizations.

Article 3: Relation to the AGU and AMS--(1) This society is organized under the provisions of the Constitution and By-Laws of the American Meteorological Society and the Statutes and By-Laws of the American Geophysical Union.

(2) In case of conflict between this Constitution and By-Laws and those of the national organizations, the latter shall take precedence.

(3) Before amendments or additions to this Constitution and By-Laws become effective, they shall be approved by the parent organizations.

(4) The national headquarters of the AMS and AGU shall be notified of the plans and proceedings of the local society.

Article 4: Members--Any person interested in the aims of the AGU, the AMS, or both, may be elected to membership. Any member of the AGU or AMS national organizations shall be eligible to membership without election.

Article 5: Election of Members--Application for membership will be reviewed by the executive committee. An applicant who is not a member of either the AGU or AMS national organizations must receive the majority vote of all members present at a regular meeting, provided further that there is a quorum as prescribed in Article 11.

Article 6: Officers--(1) The officers of this organization shall be a President, a Vice-President and a Secretary-Treasurer,

(2) These officers shall discharge the usual duties of the offices to which they are elected.

(3) The officers of this organization shall be members of either the AGU or AMS national organizations.

Article 7: Executive Committee--(1) The officers, the last ex-president, and two councilors, to be elected in the manner specified in Article 8, shall constitute an Executive Committee, which shall have general charge of the affairs of the organization.

(2) The Executive Committee should be constituted so as to give adequate representation to the following scientific fields: Meteorology, Oceanography, Hydrology, Seismology, Volcanology, Terrestrial Magnetism and Electricity, Tectonophysics, and Geodesy.

Article 8: Election of Officers--(1) The officers and one councilor of the organization shall be elected by secret ballot at the annual meeting each year. At least one month prior to the meeting preceding the annual meeting the President shall appoint a nominating committee of three. The committee shall obtain the consent of the nominees, and report such nominations to the secretary before the meeting preceding the annual meeting. These nominations shall be presented to the membership at this meeting and further nominations may be presented from the floor at this time. The nominations shall then be closed. The secretary shall prepare a ballot and submit it to the membership at least two weeks before the annual meeting. The membership may cast their ballot by mail or at the annual meeting, with the stipulation that only those ballots which reach the secretary by the annual meeting shall be counted. The ballots shall be counted and the names of the

newly elected officers announced at the annual meeting. A majority of all votes cast shall be necessary for election, provided further that the total number of members voting is not less than the quorum prescribed in Article 11. In case of failure to secure a majority for any office, the members present shall ballot a second time on the two (or if there is a tie for second, three) highest names.

(2) The term of office for the President and Vice-President shall be one year, and neither shall be eligible to succeed himself. The term of office for the Secretary-Treasurer shall be one year and for Councilors two years. One Councilor shall be elected each year except for the first election after the adoption of this constitution, at which time two Councilors shall be elected, one to serve for a term of one year and the other for two years.

(3) If an office for any reason becomes vacant, the vacancy shall be filled by the Executive Committee for the remainder of the term.

Article 9: Affiliation--(1) This society may, at the discretion of its Executive Committee, become affiliated with or otherwise cooperate with any other organizations which have an interest in its objects, provided that such affiliation or cooperation involves no conflict with other provisions of the constitution or by-laws of this society, and provided that such affiliation or cooperation shall either be of benefit to this society or extend the service of the society to the community.

(2) Representatives of this society to other organizations with which it shall become affiliated or otherwise cooperate shall be appointed by the President with the approval of the Executive Committee.

Article 10: Amendments--No part of this constitution shall be amended or annulled, except by a vote taken at a regular meeting of the organization, subsequent to the meeting at which the amendment is proposed, in the following manner: Any proposed amendment to this constitution, accompanied by a proper ballot form, shall be submitted to all members of the organization at least two weeks in advance of the meeting at which such amendment is to be considered. Every ballot marked by a qualified voter to indicate his vote and returned to the secretary in a sealed envelope, bearing the name of the voter, shall be counted at the meeting. A ballot, properly marked and endorsed by a qualified voter, may be cast in person at the meeting. The proposed amendment shall require the affirmative votes of not less than two-thirds of all members voting; provided further that the total number of members voting is not less than the quorum prescribed in Article 11. The amendment shall be adopted upon approval by the National Headquarters of the AGU and AMS.

Article 11: Quorum--The quorum required to carry on the business of the organization shall be as follows: (a) amendment of the Constitution: a majority of the total membership; (b) amendment of the By-Laws and election of officers: one-third of the total membership; (c) other business, including election of new members: fifteen members.

Article 12: Adoption of By-Laws--By-Laws to this Constitution shall be adopted as necessary by majority vote of all members voting, provided further that the total number of members voting is not less than the quorum prescribed in Article 11.

BY-LAWS

Section 1: Dues--(1) The annual dues shall not exceed one dollar, the exact amount to be fixed by the Executive Committee. The dues are payable to the Secretary-Treasurer on the first of September.

(2) If the dues of any member remain unpaid beyond a year, the Executive Committee, after due notice, shall remove the name of such member from the list of members.

Section 2: Meetings--At least four regular meetings of the organization shall be held each year, at such times and places as may be designated by the Executive Committee. One of these, to be called the annual meeting, shall be held on a day to be determined by the Executive Committee, in the month of September. Notices of the time, place and purpose of each meeting shall be sent by the Secretary to all members of the organization.

Section 3: Meetings of the Executive Committee--(1) The President shall convene the Executive Committee whenever the affairs of the organization require it.

(2) A request in writing from three members of the organization shall make the convening of the Executive Committee obligatory.

(3) The quorum of the Executive Committee shall be a simple majority of the total membership of the committee. The committee may invite any member of the organization to fill temporarily the place of an absent committee member.

SPECIAL ANNOUNCEMENTS

Transactions publication plans--Just as we were making up the February, 1955, issue of the Transactions for the printer, unofficial word came that our application for a grant to the National Science Foundation had received approval to the extent of $4000 for the year 1955. This grant was given to us on our application in order that we may get caught up on our increasing backlog of the Transactions and once again reduce the average interval from receipt of a paper to its publication to an average of about six months instead of the ten- to twelve-month figure which has been common for the last year or two, and with the understanding that the AGU would take steps to increase its income. Accordingly, the February issue of the Transactions was increased by thirty-two pages to a total of 192, and it is anticipated that within the available fund we will continue the larger size issue until we catch up to the six-month interval.

As you will note in the minutes of the Executive Committee meeting of December 4, published in the February issue of the Transactions, pages 156-168, particularly page 162, it is the general plan to change the format of the Transactions as of February, 1956, justifying the right-hand margin and otherwise improving the appearance by the use of more and different type fonts. Inasmuch as these changes and the maintenance of a six-month publication interval will involve some additional cost, it is the plan also to accept dignified display advertising germane to the general field of geophysics (word regarding prospective advertisers will be appreciated), and increase the price of reprints somewhat. Many journals have a per-page charge of $5 to $10 per page and then supply a limited number of reprints without charge; our policy has been to supply reprints at cost so that no part of the cost of publication has been assessed against the author or his organization. The new schedule of prices of reprints amounts, in effect, to a per-page charge of about $2.50.

The Executive Committee decided that it was imperative in the interests of the development of geophysics and the progress of the AGU that the changes in format be made, and it was in part for these purposes that it requested the authority of the membership to have greater latitude in meeting these problems than the Statutes and By-Laws as written provided. As set forth in the Tellers' report on page 374 of this issue, well over 90 per cent of the membership voting on the recent amendments to the Statutes and By-Laws gave approval to the changes requested. The officers of the Union and its Executive Committee appreciate this vote of confidence. Be assured that the policies of the past will prevail, these being, among other things, to hold the dues to the lowest possible level in the interests of the widest possible dissemination of American geophysical literature. At the same time, we want our Transactions to be in a form that every member may be proud to retain on his shelves.

North Central Regional Meeting to be held in Iowa City, Iowa, June 16-17, 1955--Plans are under way for this Regional Meeting to be immediately following the close of the Hydraulics Conference being arranged by the Iowa Institute of Hydraulic Research. Word of your plans or desires to participate should be sent to Regional Chairman M. C. Boyer (College of Engineering, Iowa City, Iowa) as promptly as possible, along with the title and abstract of any paper that you want to present.

Meeting in Honolulu, November 15-17, 1955--The Geophysical Society of Hawaii (Mid-Pacific Regional Branch, AGU) is planning a three-day meeting to be held in Honolulu, November 15-17, 1955. This group has been active for about three years under the general framework of the Pacific Southwest Regional Branch, with evening meetings several times a year. It has recently become the Mid-Pacific Region of AGU, serving also as a branch of the American Meteorological Society. This is the first of their general program meetings and it is anticipated that their meeting will involve various phases of seismology, meteorology, oceanography, volcanology, and hydrology. Interested persons should watch Special Announcements for further word. Those desiring to take part in the program should get into touch with John F. Mink, President (P. O. Box 48, Honolulu), or Lawrence E. Eber, Secretary (P. O. Box 3166, Honolulu).

Southeastern Regional Meeting, to be held in Atlanta, Georgia, December 26-28, 1955--Plans are being formulated for the first Southeastern Regional Meeting, to be held in conjunction with the AAAS meeting in Atlanta during the week between Christmas and New Year, probably December 26-28. This will include an extensive Symposium on the International Geophysical Year, 1957-1958, and a general program now in the planning and arranging stages. A letter with details will be sent to all members in the Region in due course. In the meantime, members are urged to make plans to attend. Papers bearing on any aspect of the broad field of geophysics are invited. Send titles and abstracts and other word of your plans to attend to Werner A. Baum (Chairman of the Southeastern Regional Committee), Department of Meteorology, Florida State University, Tallahassee, Florida.

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LETTER OF THE PRESIDENT

To the Membership of the
American Geophysical Union

Dear Fellow Members:

The forward-looking steps taken by the membership during the past year have gone a long way toward fulfilling the objectives for which the American Geophysical Union was founded. In the minds of the founders the Union had a very important role to play both on the international and national scene.

Internationally the Union was to be the Section for the United States of America of the International Union of Geodesy and Geophysics and the individual Sections of the American Union were to be the American Sections of the corresponding international associations of the IUGG.

Nationally the American Geophysical Union, acting through its Executive Committee, was to be the Committee on Geophysics of the National Academy of Sciences-National Research Council and secondly, the AGU was to be a *union* in the sense of IUGG, not a *society*, thus bringing together for consultation and cooperative effort the members of all the geophysical societies in the United States and in fact all the workers in the scientific and engineering fields of geophysics who speak the common language of mathematical formulation.

At first the American Geophysical Union was modestly financed by the NAS-NRC; but in the days of the great depression, when support was difficult to secure, the AGU was told to finance its own way with the help of a small annual grant from the NAS-NRC. Through the energetic efforts and provident foresight of our Honorary President, Dr. John A. Fleming, the Union was successful in expanding the membership to a point where the annual assessments on the members not only supported its minimum international and national activities but permitted the gradual expansion of its *Transactions* from a mimeographed report of its annual meetings into a scientific journal of international repute.

The annual assessments on the membership were called *dues*. This readily understandable name has given rise to misunderstanding in the minds of some who have cited the name as proof that the AGU is just another scientific society to be coordinated with the American Meteorological Society, the Society of Exploration Geophysicists, the Seismological Society of America, and all the other professional and scientific societies in the various fields of geophysics. To clarify this situation and remove this source of misunderstanding the AGU at its business meeting held May 4, 1955, voted to recommend to the Standing Committee on Statutes and By-Laws that a change in name from "dues" to "annual contribution" in the Statutes be referred to the membership.

This same misunderstanding of the role of the AGU has been clouding its relationship to the NAS-NRC for some years past. This was felt to be so unfortunate that President Walter H. Bucher, at the instance of the Executive Committee of the Union, appointed a special committee to study the matter under the chairmanship of Dr. F. W. Reichelderfer. This committee held several meetings and presented a report [*Trans.*, v. 35, pp. 347-348]. When further complications arose in connection with representation at the Tenth Assembly of IUGG in Rome, Chairman W. W. Rubey of NRC asked the undersigned to be chairman of a special committee to bring in recommendations which were graciously accepted by NRC.

However, the issues involved seemed to be of such importance that your President felt that the special committee should be continued under the chairmanship of Captain Lloyd V. Berkner. The report of this committee was printed for the consideration of the AGU membership in the August, 1954, issue [pp. 691-698] of the Transactions. The special provisions that it recommended were favorably considered by the Standing Committee on Statutes and By-Laws and were adopted by the Executive Committee at its meeting December 4, 1954. Such provisions as required revision of the Statutes and By-Laws were referred to the whole membership by mail ballot in February, 1955, and received an overwhelmingly favorable vote. One of these provisions is the creation of a Standing Committee on International Participation which will cooperate closely with the Office of International Relations of the NAS-NRC.

Another step toward enhancing the stature of the American Geophysical Union both at home and abroad is the contemplated change in the appearance of the Transactions. Beginning with the January, 1956, issue the Editorial and Publication Committee will go over to an attractive, letterpress page. In order to finance this improvement five steps have been taken. First, dignified and appropriate advertising is being solicited [see Special Announcement, page 569, and the advertisement on page 572 of this issue of the Transactions]; second, a grant of $4000.00 was secured from the National Science Foundation to finance the transition from a backlog of one year for papers awaiting publication to the really short interval of six months; third, the Executive Committee has authorized a modest increase in the annual contribution of members from seven to eight dollars; fourth, a small increase in the cost of reprints has been instituted; and fifth, a small increase in the subscription rate for 1956 is being made.

Your President believes that we are now on our way to a new era of usefulness and prestige for the American Geophysical Union.

Yours sincerely,

James B. Macelwane, S.J.

James B. Macelwane, S.J., President
American Geophysical Union

TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

Volume 36 June 1955 Number 3

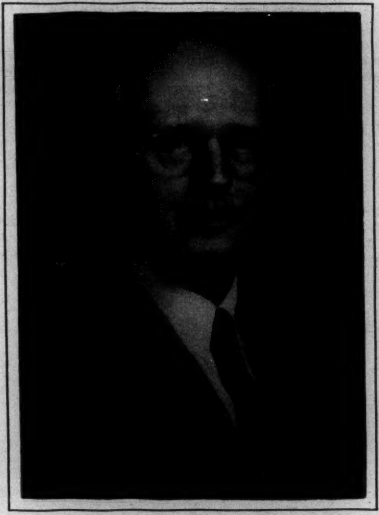
SEVENTEENTH AWARD OF THE WILLIAM BOWIE MEDAL

CITATION

Maurice Ewing

Mr. President, Members and Guests of the American Geophysical Union: It is a great privilege to present to you the Committee's nomination for the Seventeenth Award of the William Bowie Medal.

Walter Bucher personifies the unselfish cooperation in research which was so outstanding a characteristic of William Bowie. The lively personality, the broad interest in all cultural and scientific matters, and the remarkable warmth of friendship are traits shared by both of these great men. It was natural that these men respected and admired each other and cooperated on many important projects.



Walter Hermann Bucher
Recipient, Seventeenth Award,
William Bowie Medal - May 3, 1955

Walter Bucher was trained as a paleontologist, heir to the great traditions of Heidelberg and to an enduring interest in Alpine geology.

His publications, which reflect a systematic evolution and logical development of primary interest from littoral zoology through sedimentation and sedimentary petrology to cryptovolcanic structures and finally to an attempt to interpret tectonic processes on a global scale, have given inspiration to geologists and geophysicists throughout the world. His impressive record of publications is no measure of his true influence on the studies upon which all of us are engaged.

Those who have had the privilege of working with him or studying under him know that his greater influence has been in his contagious enthusiasm for natural science. A school of geology has been built around him. Many of those present tonight are indebted to him for generous contribution of encouragement and advice.

Despite these demands upon his time, he has served as Chairman of the Division of Geology and Geography of the National Research Council and as President of the American Geophysical Union and of the Geological Society of America, and in many other important capacities.

There is probably no one present whose indebtedness to this man is greater than my own.

Mr. President: Your Committee has nominated a most worthy addition to the distinquished company of William Bowie Medalists.

Presentation by President James B. Macelwane

Professor Walter H. Bucher, tectonophysicist, structural geologist and scientific statesman, world leader in the study of cryptovolcanic phenomena, ambassador-at-large of American Science, close friend and disciple of William Bowie, promoter of understanding cooperation between scientific geologists and scientific geophysicists, between geological engineers and geophysical engineers, with their divergent outlooks, interests, methods and languages, a great President of the American Geophysical Union whose term of office was destined to fall in a critical period of the history of the Union and who so capably vindicated the unique place of the Union on the foreign and domestic scene and its role, not as a scientific Society, but as the American section of the International Geodetic and Geophysical Union and through its Executive Committee, as the Committee on Geophysics of the National Academy of Sciences-National Research Council. It is indeed an honor and pleasure, Professor Bucher, to confer on you the William Bowie Medal.

Response and Acceptance by Walter H. Bucher
(by telegram read by John Putnam Marble)

I appreciate deeply the honor of receiving the medal which bears the name of the man whose personal encouragement meant very much to me in crucial days of my development. I accept the medal humbly in the hope that its bestowal on a geologist will be justified by ever-increasing mutual confidence and genuine collaboration between geophysicists and geologists.

Transactions, American Geophysical Union Volume 36, Number 3 June 1955

EXTRATERRESTRIAL MATERIAL IN DEEP-SEA DEPOSITS

Taivo Laevastu and Otto Mellis.

(Contribution No. 186 from the Department of Oceanography
of the University of Washington)

Abstract--Cosmic black spherules have been separated quantitatively from a long sediment core taken at a depth of 5000 m from the equatorial Pacific Ocean. Their size and mass distribution correspond with theoretical values obtained by Öpik [1951]. Based on this quantitative examination and PETTERSSON's [1952] determination of the probable rate of sedimentation in this area, it is estimated that about 125 tons of black cosmic spherules reach the Earth per year. Chemical analyses in this core average 0.056 pct NiO and 6.21 pct Fe_2O_3 [PETTERSSON and ROTSCHI, 1952]. These values are too great to be accounted for by the minute quantities of spherules present. Instead, the Ni and Fe appear to be derived in part from coprecipitation from sea water. The time of geochemical circulation of Ni and Fe in sea water has been estimated at 2200 and 280 yr respectively.

Introduction--Cosmic black particles in deep-sea sediments have been described previously by MURRAY and RENARD [1891], BUDDHUE [1950], and ÖPIK [1951]. In order to supplement our knowledge of the occurrence of extraterrestrial materials in sediments and to obtain quantitative estimates of their abundance and rate of deposition, three long deep-sea cores obtained during the Swedish Deep-Sea Expedition of 1947-48 were analyzed for materials of cosmic origin.

One of the cores (no. 72) is from the Pacific Ocean, (7° 38'S, 152° 53' W, depth 5000 m) and the other two (no 275 and 299) are from the Atlantic Ocean.

Core 72 consists of homogeneous, chocolate brown red clay and a minor amount of radiolarian tests. Core 275 is similar in composition, consisting of Atlantic red clay, whereas core 299 is a foraminiferal ooze.

Separation of magnetic particles--Materials of probable cosmic origin that have been recognized in deep-sea sediments consist of black spherules, brown chondrites, and metallic particles. Because all these materials are ferromagnetic, their separation was carried out magnetically. An electromagnetic separator manufactured by S. G. Franz Co., of Trenton, N. J., was used. The procedure consists of mixing from 50 to 200 g of wet sediment with about 600 to 800 ml of distilled water. This mixture is poured three times through the screens of the separator. Thereafter, the clay is cleaned from the separator, and the screens are washed carefully in distilled water. The magnetic particles are gathered from this water by a strong electromagnet, rinsed into a weighing bottle, and dried.

To determine the accuracy of the separator, a weighed amount of small Fe spherules was mixed with a sample of sediment from which the natural spherules had been removed previously. When passed twice through the magnetic separator, between 91 and 98 pct of the artifical spherules was recovered. The average recovery, as determined from five such separations, was 95.3 pct.

In similar studies by previous investigators [MURRAY and RENARD, 1891], the cosmic particles have been separated from the sediment by a strong hand magnet or a bottom magnet. An attempt to separate the artificially prepared spherules by these methods resulted in recoveries that ranged from 1.5 to 10.7 pct. It is concluded, therefore, that previous estimates of the amount of cosmic material in deep-sea sediments are far too low.

The magnetic particles were mounted on glass slides covered with a thin film of gelatin and examined under the microscope.

Constituents of the magnetic separates--Of the separates of the three cores, only those from core 72 from the Pacific Ocean contained sufficient cosmic material for quantitative study. Core 275 from the Atlantic contained visible cosmic material, but the abundance of magnetite particles, which tend to mask the cosmic grains, prevented a reliable quantitative examination. Core 299 contained no visible material of cosmic origin. A flood of magnetite particles was all that could be observed in the separates from this core. An attempt to separate the magnetite from the cosmic materials with heavy liquids was unsuccessful. The failure of this type of separation was caused apparently by (1) the small amount of material available, (2) the minute size of the particles, and (3) the almost identical specific gravities of magnetite and cosmic particles.

The octahedral shape and sharp edges of some of the magnetite grains suggest that they are authigenic.

Particles of cosmic origin recognized in the magnetic fraction of core 72 consist of black spherules ranging in size from 10 to 230 μ and small irregular grains with diameters generally less than 40 μ. Both the spherules and the smaller fragments have a corroded surface with metallic luster (Figs. 1 and 2). Some of the grains are coated with small patches of yellowish material which probably consists of Fe and Mn compounds. No chondrite was recognized in any of the material examined. Surface depressions similar to those described by MURRAY and RENARD [1891] could be recognized only in a few specimens. Many of the spherules, when subjected to the pressure of a separation needle, broke without deformation.

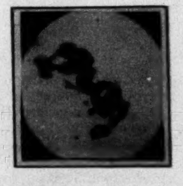


Fig. 1--Photomicrograph of two black spherules, 50 and 70 μ

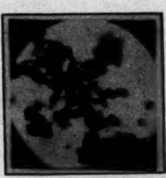


Fig. 2--Photomicrograph of the surface structure of a black spherule

Determinations of the quantity and size distribution of the cosmic particles were possible only for the spherules. The irregular particles of cosmic origin were too small and too highly contaminated with unidentifiable magnetic dust for quantitative study.

Size and volume distribution of the black spherules--Size measurements were made on 880 black spherules from core 72. The results of this study, presented in Figure 3, show that (1) the diameter of the grains ranges from 10 to 230 μ, (2) the number of particles decreases as the diameter increases, and (3) the combined volumes of the grains in each size grade are nearly constant.

The absence of spherules with a diameter greater than 230μ is in agreement with theoretical considerations of ÖPIK [1951]. According to his calculations, based on the collision theory of cosmic bodies and the Poynting-Robertson effect, essentially all cosmic particles greater than 250 μ in diameter are intercepted by the planet Jupiter and therefore do not reach the Earth. The decrease in number of particles with increasing size corresponds with the theory of the size distribution of meteoric dust made by ÖPIK [1951].

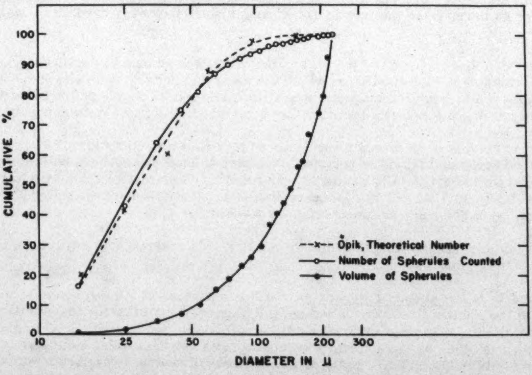


Fig. 3--Cumulative number (100 pct = 880) and computed volume (100 pct = 158 × $10^6 \mu^3$) of black spherules from Core 72, grouped in 10 μ intervals

The studies of BUDDHUE [1950] of spherules collected from rain water and air likewise show that they are concentrated in the small size-grades. In fact, the average diameter of particles analyzed by Buddhue is notably smaller than the value obtained from present studies. This difference may be due (1) to solution of small particles in sea water during sedimentation, and/or(2) to difficulty in separation and counting small spherules in the magnetic fraction of the marine sediment.

Although the number of smaller spherules counted in the marine sediments is probably too low, it is clear from Figure 3 that this error has little effect on the mass distribution of the spherules. The small spherules, although great in number, contribute very little to the total mass.

Rate of deposition of the black spherules--The number of black spherules and their distribution in the top three meters of core 72 are shown in Figure 4. According to this analysis, there is an average of 1200 spherules/kg of dry sediment in the top three meters of the core. The average diameter of all spherules is 44 μ, the median grain size is 70 μ, and the average particle volume is $1.79 \times 10^5 \mu^3$.

Using a specific gravity of 5.2 for the spherules, we find an average of 1.1 mg of spherules/kg of dry sediment. According to PETTERSSON and ROTSCHI [1952], the rate of sedimentation, determined from radium analyses of core 72, is 0.4 mm/1000 yr. Calculations based on this estimate show that the rate of deposition of dry sediment is about 22 mg/cm^2/1000 yr. Using this value and the quantitative measurements on the number and weight of the spherules, it is estimated that 264,000 spherules with a weight of 0.246 g accumulate on each sq km of the Earth's surface per year. Assuming that the rate of deposition of spherules on the deep-sea floor is typical of other areas of the Earth, it is estimated that approximately 125 tons of spherules are contributed to the Earth's surface each year. This estimate, based only on black spherules, is about one-fourth of SCHWINNER's [1936] estimate of the total contribution of all types of meteoric materials.

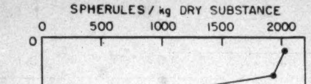


Fig. 4--Concentration of black spherules in upper three meters of Core 72

The Ni and Fe content of deep-sea deposits and of extraterrestrial material--It has been assumed by PETTERSSON and ROTSCHI [1952] that the Ni content of deep-sea deposits originates partly from extraterrestrial material. This assumption is questionable because (1) no correlation has been found between the amount of black spherules present in the core No. 72 (Fig. 4) and the Ni content of the same core, presented by PETTERSSON and ROTSCHI [1952], and (2) the total amount of black spherules in the sediment is smaller than one part per million and therefore cannot contribute considerably to the Ni content, which is several orders of magnitude higher.

In order to calculate the geochemical circulation of Fe and Ni in sea water, the following average values were taken: water content of red clay 60 pct, rate of sedimentation 3 mm/1000 yr, Fe and Ni content of red clay 1200 mg at/kg and 4.25 mg at/kg, respectively. Computations based on these values give 192 μg at Fe and 0.68 μg at Ni per cm^2/1000 yr. On the assumption that both these elements are derived from sea water (Table 1), one can compute that the approximate time for the geochemical circulation in sea water is 280 yr for Fe and 2200 yr for Ni. These values correspond reasonably well with KULLENBERG's [1953] estimate of 300 yr for the geochemical circulation of lutite in sea water.

Considering the values for the geochemical circulation of iron and nickel and the rate of deposition of red clay, it becomes obvious that the spot samples, taken in every 10 cm in the sediment core, do not show the real variations in the amounts of Fe and Ni with time. The variations in the amount of the element in the sediments are dependent on the supply, but the supply is influenced by the intensity of the weathering and transport into the sea. These factors could have varied considerably with time.

The average content of Fe and Ni and the ratio Fe/Ni for several geochemical constituents are given in Table 1. Of the common rocks and sediments listed, sedimentary rocks of shallow water origin have the highest Fe/Ni ratio and red clay the lowest. The Fe/Ni ratio for average igneous rocks is intermediate in value. From these ratios, it appears that the high content of Ni in red clays may be accounted by the leaching of Ni from sedimentary rocks of shallow water origin and from igneous rocks. This conclusion is in agreement with that of WISEMAN and SMALES [1954] who conclude that igneous rocks are the ultimate source of Ni in deep-sea sediments.

In core 72, taken in the middle of the Pacific Ocean far from any terrigenous source and where the rate of sedimentation is very low, the Fe/Ni ratio of the red clay approaches the low Fe/Ni ratio of sea water (Table 1). The correspondence of these ratios suggests, therefore, that the Fe and Ni in this red clay are influenced by coprecipitation from the sea water. Important support to this conclusion is gained from the work of ISHIBASHI [1953] who has used Fe with considerable success as a collector of Ni in the determination of the concentration of Ni in sea water.

Table 1--Fe/Ni ratios in different geochemical constituents

Substance	Fe	Ni	Fe/Ni
	mg at/kg	mg at/kg	
Meteorites [WATSON, 1941; quoted by RANKAMA and SAHAMA, 1949]	5700	354	16
Igneous rocks [GOLDSCHMIDT, 1937; quoted by FLEISCHER, 1953]	895	1.7	526
Sedimentary rocks [elements, RANKAMA and SAHAMA, 1949; rock ratio, CLARKE, 1924]	706	0.34	2080
Average red clay [Fe, CLARKE, 1924; Ni, MALJUGA, 1939]	1200	4.25	282
Core 72 [PETTERSSON and ROTSCHI, 1952]	877	7.5	117
Sea Water [Fe, LEWIS and GOLDBERG, 1954; Ni from an unpublished study by T. LAEVASTU and T. G. THOMPSON]	1.43×10^{-4}	3.9×10^{-5}	37

GOLDBERG [1954] has recently discovered a relationship between the quantities of Ni and Mn in red clay which has led him to the conclusion that Ni is also coprecipitated with Mn. From the results of our studies it appears, however, that Fe, which is more abundant than Mn in sea water, has been the chief coprecipitator of Ni.

Conclusions--(1) The distribution of the size and volume of the cosmic black spherules is represented in Figure 3. The distribution corresponds fairly well with what would be expected from the theories of Van de Hulst and ÖPIK [1951].

(2) The amount of cosmic black spherules reaching the surface of the Earth per year is calculated at 125 tons.

(3) Cosmic black spherules apparently do not influence the Ni content of deep-sea deposits to a very great extent.

(4) The amount of Ni in deep-sea deposits far from land is probably controlled chiefly by coprecipitation with Fe and to a lesser extent with Mn.

(5) The geochemical circulation time of Ni in sea water is estimated at about 2200 yr and of Fe 280 yr.

Acknowledgments--The authors wish to express their sincere thanks to H. R. Gould, R. H. Fleming, and Wayne V. Burt for valuable criticism and editing of this paper and to H. Pettersson for providing the material and for his encouragement in this work. Part of this work was carried out in Oceanografiska Institutet in Göteborg.

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DISCUSSION

Ernst J. Öpik (Armagh Observatory, North Ireland)--The observed distribution of the diameters of the spherules cannot be well represented by Öpik's theory with constant velocity, w. However, assumption of a moderate spread in velocity leads to satisfactory agreement. The dotted curve in Figure 3, called 'Öpik, Theoretical Number,' corresponds to the following frequencies of three discrete values of the velocity:

W, km/sec	11.5	13.2	16.9	All
Relative frequency, pct	33.3	16.7	50.0	100.00

With these, the theoretical frequency of diameters is found as follows:

Diameter, $\mu \leq$	17	25	49	55	89	165	300
Cumulative frequency, pct	23.5	39.7	72.6	79.4	94.7	99.6	100.0

With more detail in the velocity distribution, almost perfect agreement with the observed figures could be obtained, although even in such a form the agreement is very close.

A low value of and a low dispersion in the velocities is definitely indicated, corresponding to cosmic dust circling the Sun in direct orbits of low eccentricity. Of course, spherules corresponding to high velocities are too small to be detected (?).

Transactions, American Geophysical Union Volume 36, Number 3 June 1955

PRELIMINARY STUDIES OF THE DISTRIBUTION OF AURORAS IN ALASKA

C. T. Elvey, Harold Leinbach, Joan Hessler, and John Noxon

Abstract--The analysis of auroral observations for 1951-53 from five stations spread over Alaska shows a zone at geomagnetic latitude 68° for which the incidence of auroras is independent of magnetic activity. At geomagnetic latitudes south of 67°, the incidence of auroras is markedly dependent upon magnetic activity.

The credit for defining the auroral zone is sometimes given to FRITZ [1881], who constructed a map of isochasms, or lines of equal visibility of auroras; however, LOOMIS [1865, 1868], 21 years earlier than Fritz, published a chart showing the distribution of auroras in the northern hemisphere. VESTINE [1944] brought up to date the geographical distribution of auroras, incorporating the many series of observations obtained during the Polar Years 1882-83 and 1932-33. He applied corrections for cloudiness and presented charts showing the estimated percentage-frequency of clear nights characterized by aurora.

As has been repeatedly pointed out, the primary difficulty with this type of datum is the lack of resolution in the distribution, especially in latitude. An inspection of Vestine's diagram showing the frequency of visible aurora versus geomagnetic latitude gives the auroral zone a width of approximately 14° at the level of 50 pct auroral frequency. Furthermore, in approaching the zone from the south side, the auroral frequency changes from a value of 34 pct at geomagnetic latitude 61° to 68 pct at 64° --a doubling in three degrees of latitude (333 km). With transparent atmospheres such as prevail in the arctic winter, an observer can distinguish an aurora whose lower edge is, say, two degrees above an unobstructed horizon. Using this criterion, an aurora whose lower edge is 100 km high can be seen from stations dispersed over a span of 1940 km or 17.5° of latitude. Under these favorable conditions, an observer at College could see an aurora over any part of mainland Alaska or over any but the furthest parts of Yukon Territory, Canada. It is apparent that observations made, say, at College, may report auroras which occur across the major portion of the auroral zone.

During the two seasons September through April for 1951-52 and 1952-53, systematic observations of auroras were made in Alaska at Point Barrow, Nome, Northway, Sheep Mountain, and College. The observations were made at 15-minute intervals during each hour of darkness at each station and were plotted on a chart of the sky, using zenith distance and azimuth as polar coordinates. Records of clouds were kept, thus making it possible to determine the frequency of occurrence of auroras in any part of the sky. The observations at College, made by professional personnel, are considered to be more reliable than the rest. The reliabilities of the observations at Northway and Sheep Mountain are readily tested by the observers at College, for the auroras appearing at the zenith for the two stations are well above the horizon as seen from College. This is not true of the stations at Nome and Point Barrow, but if auroral activity at either of these two stations extends toward the eastern horizon, as for example, arcs through their zeniths, the arcs would also be observable from College. Investigation shows that for the period discussed the Northway observations were unreliable after midnight and the Point Barrow observers did not record the fainter auroras.

With these uncertainties in mind, the zenith observations of auroras for each of the stations were analyzed by ELVEY, LEINBACH, and HESSLER [1953] to show the nocturnal variation in the frequency of auroras. The data are shown graphically in Figure 1. From these observations we may conclude tentatively that in northern Alaska the maximum of auroral activity centers around midnight, whereas at College the activity increases steadily until midnight and then remains more or less constant through the remainder of the night.

This paper continues the analysis of the observations made at the five Alaskan stations. STØRMER [1926, 1953] and others [MITRA, 1952] have measured the heights to the lower border of a large number of auroral forms. Although there is a rather large range in height, the greatest frequency is at a height of 100 km for all forms. In our statistical studies we have assumed that height and have computed the zenith distance at which each parallel of geomagnetic latitude projec-

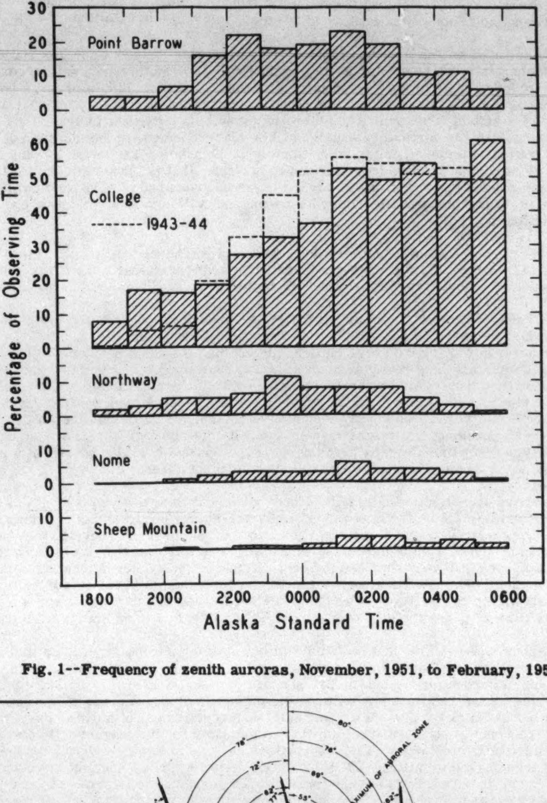

Fig. 1--Frequency of zenith auroras, November, 1951, to February, 1953

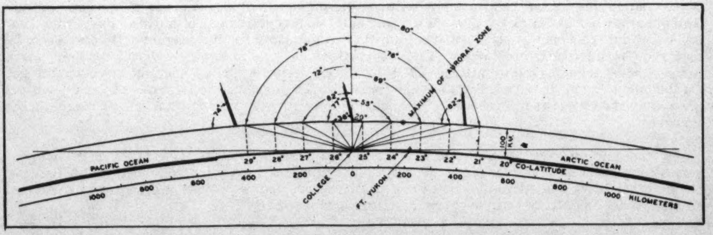
80°
78°
76°
72°
69°
82°
77°
53°
36°
20°
74°
82°
MAXIMUM OF AURORAL ZONE
100 KM
PACIFIC OCEAN
29°
28°
27°
26°
25°
24°
23°
22°
21°
20° CO-LATITUDE
ARCTIC OCEAN
1000
800
600
400
200
0
200
400
600
800
1000 KILOMETERS
COLLEGE
FT. YUKON

Fig. 2--Construction of successive parallels of geomagnetic latitude at 100-km altitude, showing zenith distance as observed at College, Alaska

ted to such a height would cross the magnetic meridian (Fig. 2). As may be seen, the span in zenith distance for the one-degree zone of latitude in which the observer is located is 56°, whereas a band of five degrees of latitude is encompassed in the ten-degree viewing angle nearest the horizon.

Accordingly we confine this study to observations with zenith distance less than about 80°, that is, four or five degrees of latitude along the magnetic meridian north or south of each station. For College, the range in geomagnetic latitude is from 61° to 69°, or in colatitude, 21° to 29°.

We have selected as a unit of geographical area over which to count auroras a zone of one degree in geomagnetic latitude. Any aurora observed to be over this area will be counted. By this choice one loses some of the finer details of auroral displays. For example, a homogeneous arc might be likened to a ribbon across the sky but standing on edge in the atmosphere. The distance through the ribbon, the north-south direction, may be a kilometer or less. The width of the ribbon-like structure (its vertical extension) will be many kilometers; the measure of this dimension is very difficult because there is no distinct upper boundary. The length of such a structure (the east-west extension) is often from horizon to horizon--that is, 2000 km. During the development of a simple display, the arc moves toward lower latitudes and at some critical phase may break into rays, draperies, and other complex forms and, within seconds, may spread over a large distance in latitude.

One error for which we do not correct arises as follows: The auroral arcs are thin and extend to great heights. Therefore, fainter arcs can be detected near the magnetic zenith than to the north or south, because the observer looks through a greater mass or distance of auroral light.

STØRMER [1953] has plotted the frequency of the measured height to the lower border. The spread of the heights at the 50 pct point is - 15 km, and + 18 km from the height of the maximum. Hence, those auroras which have lower borders higher than the adopted value will be recorded as closer to the station than they really are; those which have them lower will be recorded farther from the station than they are. The error increases with the zenith distance of the observation. Since we have placed a limit of 80° zenith distance for our observations, we find that 50 pct of the observations will fall within ± 65 km of the computed distance from the station, or ± 0.6° of latitude for the observations along the magnetic meridian. It thus appears that auroras observed over the zone of latitude, say four degrees to the north of the observer, really represent a partial averaging of some of the auroras appearing over the two adjacent zones.

With the above uncertainties in mind, we have attempted to so analyze our data as to minimize errors. The observational material consists of quarter-hourly observations of auroras at each of the five stations, representing in the aggregate a range of geomagnetic latitude from 58° to 74°. The frequencies of appearance of auroras over each zone of geomagnetic latitude as seen from a given station for each of the seasons and for each of the groups of international quiet and disturbed days were computed. The results are shown in Figure 3. In addition, the data from the Maud Expedition are shown for two positions of the ship: 1922-24, when the ship was in the ice pack north of Siberia and 1924-25, when the ship was at Four Pillar Island, a fixed station off the Siberian Coast.

The data show quite clearly that the visibility of any given aurora depends on the zenith distance at which it is observed, so that before the data from two or more stations can be assembled into a composite study, a correction for zenith distance will have to be determined. The curves of Figure 3 show some interesting relationships between the incidence of auroras and of magnetic activity. The observations at Point Barrow show a radically different number of auroras during the two seasons, but the frequency of appearance of auroras is the same for the magnetically disturbed days as for the magnetically quiet days. The observations at College likewise show a tendency for auroras occurring at geomagnetic latitudes 67° to 69° to be relatively independent of the magnetic activity. On the other hand, the auroras which are incident over geomagnetic latitudes 66° and southward show a marked increase in frequency of appearance of auroras during intervals of magnetic disturbance.

A possible interpretation of this effect in terms of solar-terrestrial relationships invokes a general emission of particles from the Sun, bombarding the Earth in a zone near Point Barrow. On the other hand, the sporadic streams of particles emitted by the Sun, which produce magnetic storms, enter the Earth's atmosphere at latitudes lower than 67°.

A more extensive set of auroral data is being collected during the current auroral season, 1953-54. The data are being assembled by the same three-hour periods for which the geomagnetic K index is derived, and the analysis of the data with regard to the K index is being undertaken.

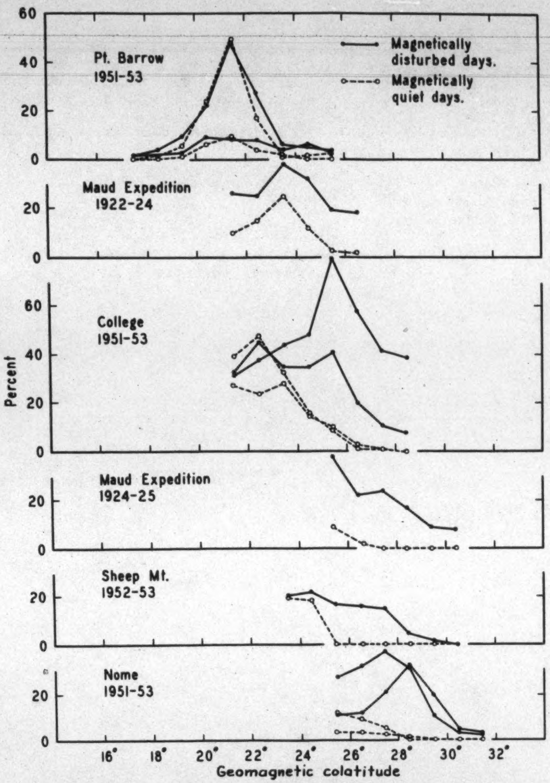

Fig. 3--Incidence of auroras versus geomagnetic colatitude

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SOLUTIONS OF THE TWO-DIMENSIONAL DIFFUSION EQUATIONS

Wellington Rounds, Jr.

Abstract--General solutions of the two dimensional diffusion equation are derived following the work of Sutton and the profiles of Deacon. These solutions apply to (1) diffusion of gases and aerosols from sources infinite in cross-wind extent located at arbitrary heights and having arbitrary initial distributions; (2) diffusion of particles with non-zero free fall velocity; and (3) diffusion of gases and aerosols under an atmospheric lid as at the base of an inversion. These solutions are then applied to several types of sources and the down-wind concentrations are presented in graphical form.

Introduction

The differential equation describing steady state, gradient type diffusion from a source infinite in the cross-wind direction and oriented perpendicular to the mean wind flow is

$$U(Z)\,(\partial C/\partial X) = (\partial/\partial Z)\,[K(Z)\,(\partial C/\partial Z)] - \Omega\,(\partial C/\partial Z) \quad \ldots\ldots\ldots\ldots \quad (1)$$

where the term $(\partial/\partial X)\, K_x\, (\partial C/\partial X)$ has been neglected in comparison with $U(Z)\,(\partial C/\partial X)$ and

X = down-wind distance
Z = height
C = concentration at (X, Z)
$U(Z)$ = wind speed
$K(Z)$ = coefficient of eddy diffusivity
Ω = free fall velocity, positive in the positive Z direction

Roberts, in an unpublished paper, derived the following particular solution of (1) for a ground source where K and U vary as power functions of height and $\Omega = 0$.

$$C(X, Z) = \frac{Q U_1^{(m+1)/(2+m-n)-1} \exp\left[- U_1 Z^{2+m-n}/\lambda(2+m+n)^2 X\right]}{(2+m-n)^{2(m+1)/(2+m-n)-1}\, \lambda^{(m+1)/(2+m-n)}\, \Gamma_{(m+1)/(2+m-n)}\, X^{(m+1)/(2+m-n)}} \quad \ldots\ldots\ldots\ldots \quad (2)$$

The conditions satisfied by this solution are

$$U = U_1 Z^m \quad \ldots\ldots\ldots\ldots \quad (3a)$$

$$K = \lambda Z^n \quad \ldots\ldots\ldots\ldots \quad (3b)$$

$$\left.\begin{aligned} C(X=0) &= 0 \qquad & Z &\neq 0 \\ &= \infty & Z &= 0 \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots \quad (3c)$$

$$\int_0^\infty UC\,dZ = Q, \text{ the strength of the source} \quad \ldots\ldots\ldots\ldots \quad (3d)$$

$$C \rightarrow 0 \text{ as } X \rightarrow \infty \quad \ldots\ldots\ldots\ldots \quad (3e)$$

$$K(\partial C/\partial Z) \rightarrow 0 \text{ as } Z \rightarrow 0 \quad \ldots\ldots\ldots\ldots \quad (3f)$$

The solution presumes no dependence between m and n other than $2 + m - n > 0$.

CALDER [1949] adopted this solution under the following definitions of K and U which apply to a layer of constant shearing stress, τ_o

$$U = U_1 (Z/Z_1)^{\alpha} \quad \text{(4a)}$$

$$K = MU_1^{2\gamma-1} Z_1^{\alpha(1-2\gamma)} Z^{1-\alpha} \quad \text{(4b)}$$

$$M = (\epsilon/\alpha)\, \delta^{2\alpha\gamma}$$

where the parameters γ, ϵ, and δ, are defined for smooth and rough flow. Essentially Calder fits the wind profile at two points to a power law and then determines K from the expression for U such that

$$\tau_o = \rho K (dU/dZ) = \text{constant} \quad \text{(5)}$$

DEACON [1949] observed that the slope of the wind profile has the form

$$dU/dZ = aZ^{-\beta} \quad \text{(6)}$$

Assuming this form he obtained

$$K = \frac{\tau_o}{\rho (dU/dZ)} = k v_* Z_o^{1-\beta} Z^{\beta} \quad \text{(7)}$$

$$U = [v_*/k(1-\beta)]\,[(Z/Z_o)^{1-\beta} - 1] \quad \text{(8)}$$

where

v_* = friction velocity = $\sqrt{\tau_o/\rho}$
k = von Karman's constant (a value of k = 0.45 has been assumed for the computations of this paper)
Z_o = roughness parameter
β = stability parameter, $\beta > 1$, unstable; $\beta = 1$, neutral; $\beta < 1$, stable

Since Roberts' solution requires a power low wind profile, Deacon approximated (8) by

$$U = v_* q (Z/Z_o)^{\alpha} \quad \text{(9)}$$

where α and q are determined from the observed wind profile.

Deacon published comparisons of observations and calculations based on Roberts' solution with the form (7) and (9) of K and U for neutral and unstable conditions. Calder gives similar data for neutral conditions.

In this paper, a general solution of (1) with $\Omega = 0$ and valid for atmospheric values of β, α, and q is derived as is a solution with Ω arbitrary and $\beta = 1$, that is, neutral stability. These solutions apply to arbitrary initial distributions. They are then applied to several types of sources.

The forms of K and U are those of Deacon, (7) and (9), where for the purposes of illustration α and q are determined from β and Z_o by requiring that

$$\int_0^{Z_1} (9)\, dZ = \int_0^{Z_1} (8)\, dZ \quad \text{(10)}$$

and

$$\left.\frac{d(9)}{dZ}\right|_{Z=Z_1/2} = \left.\frac{d(8)}{dZ}\right|_{Z=Z_1/2}$$

These conditions lead to the implicit relations

$$2^{\alpha}/\alpha(1+\alpha) = \begin{cases} (2^{1-\beta}/1-\beta)\,[1/(2-\beta) - (Z_1/Z_0)^{\beta-1}] & \beta \neq 1 \\ \ln (Z_1/Z_0) - 1 & \beta = 1 \end{cases} \quad \ldots\ldots\ldots (11)$$

$$q = (1/k\alpha)\,(Z_1/2Z_0)^{1-\beta-\alpha}$$

which determine α and q as functions of β and Z_1/Z_0. The value of Z_1 has been taken as the height of the source in elevated source solutions and as some arbitrary height over which the major portion of diffusion occurs for ground or near ground sources. This determination of α and q does not affect the general solutions, and it is employed here as an approximation for simplicity of illustration.

It should be noted that the assumptions of a power law diffusivity coefficient and wind profile are thought to be valid over a region of constant shearing stress, τ_0. If this is correct, the solutions obtained are generally valid for down-wind distances in which the major portion of the diffusing substance is in the constant τ_0 region. In particular, the ground concentrations should be tolerably valid for greater down-wind distances.

General solutions

We make the transformations

$$\left.\begin{aligned} c &= C\,\ell\,U(\ell)/Q \\ z &= (Z/\ell^{[(2+\alpha-\beta)/2]} \\ x &= (2+\alpha-\beta)^2\,K(\ell)\,X/\ell^2\,U(\ell) \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots (12)$$

where ℓ is some convenient length, taken as the height of the source in most applications. The differential equation (1) then reduces to

$$4\,(\partial c/\partial x) = (\partial^2 c/\partial z^2) + [(1 - 2p/z) - (2\omega/z^{1-2p})]\,(\partial c/\partial z) \quad \ldots\ldots\ldots\ldots (13)$$

$$p = (1-\beta)/(2+\alpha-\beta) \qquad\qquad \omega = [\Omega/(2+\alpha-\beta)\,k v_*]\,(Z_0/\ell)^{\beta-1}$$

For $\Omega = 0$, this may be written as

$$4\,(\partial c/\partial x) = (\partial^2 c/\partial z^2) + [(1 - 2p)/z]\,(\partial c/\partial z) \quad \ldots\ldots\ldots\ldots\ldots (13a)$$

For $\beta = 1$ and $\Omega \neq 0$, we have

$$4\,(\partial c/\partial x) = (\partial^2 c/\partial z^2) + [(1 - 2\omega)/z]\,(\partial c/\partial z) \quad \ldots\ldots\ldots\ldots\ldots (13b)$$

We note that (13b) is identical in form with (13a) with p replaced by ω. Thus the differential equation of the free fall velocity problem under adiabatic (neutral stability) conditions reduces to the zero free fall velocity problem with p replaced by ω. The solutions will then be the same, and we therefore derive solutions of (13a) where

$$p = (1-\beta)/(2+\alpha-\beta) \qquad \text{when } \Omega = 0$$

$$p = \left[\frac{q(\ell/Z_0)}{(1+\alpha)\,k}\right]\frac{\Omega}{U(\ell)} \qquad \text{when } \beta = 1.$$

Eq. (13a) differs only by the constant factor four from the equation studied by SUTTON [1943] in his work on evaporation. The nature of p differs in that it may assume both positive and negative values. The restriction on p to positive values in Sutton's work is overly strict, and may be replaced by $|p| < 1$. Special attention is then required, however, in evaluating limits for $p < 0$ and in the special case $p = 0$.

Upon separation of variables, (13a) reduces to a simple combination of differential equations which is seen to include Bessel's equation in the z component. The general solution is readily determined as

$$c = z^p \exp(-\sigma^2 x/4)\, J_{\pm p}(\sigma z) \quad \ldots\ldots\ldots\ldots \quad (14)$$

where $J_{\pm p}(\sigma z)$ is Bessel's function of the first kind of order $\pm p$.

In the case $p = 0$, the solution is

$$c = \exp(-\sigma^2 x/4)\, [c_1 J_0(\sigma z) + c_2 Y_0(\sigma z)] \quad \ldots\ldots\ldots\ldots \quad (14a)$$

Application of the boundary conditions that the flux, $-K(\partial C/\partial Z)$, must be zero through the lower boundary determines c_2 as zero and thus the solution is of the same form as (14).

Multiplying (14) by the constant $\sigma J_{\pm p}(\sigma\lambda)$ where λ is arbitrary and integrating with respect to σ yields another form of the general solution

$$X_{1,2} = \int_0^\infty z^p J_{\pm p}(\sigma z)\, J_{\pm p}(\sigma\lambda) \exp(-\sigma^2 x/4)\, \sigma\, d\sigma = (2\lambda^p/x) z^p \exp[-(z^2+\lambda^2)/x]\, I_{\pm p}(2\lambda z/x) \quad \ldots\ldots\ldots\ldots \quad (15)$$

where $I_{\pm p}(2\lambda z/x)$ is the Bessel function of pure imaginary argument. The subscripts 1 and 2 refer to the positive and negative signs of the order of the Bessel function. We then define $F_{1,2}$ as

$$F_{1,2} = \int_0^\infty \lambda^{1-2p} f(\lambda)\, X_{1,2}\, d\lambda = \int_0^\infty 2f(\lambda)\, z^p \lambda^{1-p} \exp[-(z^2+\lambda^2)/x]\, I_{\pm p}(2\lambda z/x)\, d\lambda/x \quad \ldots\ldots\ldots\ldots \quad (16)$$

It can be shown that $F_{1,2}$ have the following properties

$$\left.\begin{aligned} &\lim_{X\to 0} F = f(z) \\ &\lim_{Z\to\infty} F = \lim_{z\to\infty} f(z) \\ &\lim_{Z\to\infty} [-K(\partial F/\partial Z)] = \lim_{z\to\infty} [\text{constant} \cdot z^{1-2p}(\partial F/\partial z)] = \lim_{z\to\infty} [\text{constant} \cdot z^{1-2p} f'(z)] \end{aligned}\right\} \quad \ldots \quad (17)$$

Thus $F_{1,2}$ satisfy an initial distribution $f(z)$ in the plane $X = 0$ and, if $f(z) = 0$ for all $z > z_1$, the concentration and flux at the upper boundary, $Z = \infty$, are both zero.

Employing the power series expansion for $I_{-p}(\Omega)$ and integrating term by term we obtain for F_2

$$F_2(x, z) = \exp(-z^2/x)\ \Sigma\, [b_n(x)/\Gamma_{n+1}\, \Gamma_{n+1-p}]\, (z^2/x)^n \quad \ldots\ldots\ldots\ldots \quad (18)$$

where $\Gamma(n)$ is the gamma function and

$$b_n(x) = \int_0^\infty f(\sqrt{sx}) \exp(-s)\, s^{n-p}\, ds$$

We may then readily evaluate the following limits

$$\left.\begin{aligned} &\lim_{z\to 0} F_2 = b_0(x)/\Gamma(1-p) \\ &\lim_{z\to 0} [z^{1-2p}(\partial F_2/\partial z)] = 0 \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots \quad (19)$$

Thus $c(x, z) = F_2$ is a solution of the two-dimensional diffusion equation satisfying the following boundary conditions

The source has an initial distribution, $f(z)$, in the plane $x = 0$ . . . . (20a)

If $f(z)$ is zero for all z greater than some finite z_1 the concentration at the upper boundary, $z = \infty$, is zero . . . . (20b)

If $f(z)$ is constant for all z greater than some finite z_1 the flux through the upper boundary is zero . . . . (20c)

The flux through the lower boundary, $z = 0$, is zero . . . . (20d)

The conditions (20b) and (20c) are sufficient by (17), but not necessary. Functional initial distributions which do not satisfy (20b) or (20c) may be tested by (17).

It should be noted that F_1 is also a solution. The boundary conditions along $z = 0$, which F_1 satisfy, however, are applicable primarily to evaporation problems. SUTTON [1943] gives a complete discussion of this function as well as several allied functions.

Particular source solutions

Constant concentration over a finite height interval and line sources--If the initial distribution is given as

$$\left.\begin{array}{lll} F(Z) = 0 & 0 \leq Z < A & Z > B \\ \quad\;\; = C_0 & A \leq Z \leq B & \end{array}\right\} \quad \ldots\ldots\ldots\ldots (21)$$

or graphically as in Figure 1, the solution is obtained from (18) by replacing $f(z)$ by

$$\left.\begin{array}{ll} f(z) = c_0 & a \leq z \leq b \\ \quad\;\; = 0 & \text{elsewhere} \end{array}\right\} \ldots (22)$$

The lower case here indicates that the transforms of (12) were made with ℓ equal h, the average height of the source. As C_0 is not generally known explicitly, but rather Q, the strength of the source, we determine C_0 by the continuity condition

$$\int_0^{\infty} U\,C\,dZ = Q \quad \ldots\ldots (23)$$

as

$$C_0 = Q \Big/ \int_A^B v_* q\, Z^{\alpha} Z_0^{-\alpha}\, dZ$$

$$= Q(1+\alpha)/v_* q\, Z_0^{-\alpha}(B^{1+\alpha} - A^{1+\alpha}) \quad \ldots (24)$$

and

$$c_0 = C_0 h\, U(h)/Q = (1+\alpha)\, h^{1+\alpha}/(B^{1+\alpha} - A^{1+\alpha}) \;. \; (25)$$

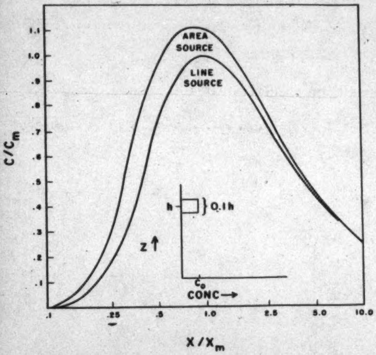

Fig. 1--Ground concentration for area source (see inset) and line source at $Z = h$; area is width 0.1h; $\beta = 1$; $h/Z_0 = 10^3$, wind profile fitted to $Z_1 = h$; units are line source maxima

Thus

$$\left.\begin{array}{ll} f(z) = c_0 = (1+\alpha)\, h^{1+\alpha}/(B^{1+\alpha} - A^{1+\alpha}) & (A/h)^{(2+\alpha-\beta)/2} \leq z \leq (B/h)^{(2+\alpha-\beta)/2} \\ \quad\;\; = 0 \quad \text{elsewhere} & \end{array}\right\} \ldots (26)$$

Substituting this value in (18) we have

$$\left.\begin{aligned} c(x,z) &= \exp(-z^2/x)\ \Sigma(z^{2n}/\Gamma_{n+1}\Gamma_{n+1-p}) \int_{Z=A}^{B} c_o\, e^{-s}\, s^{n-p}\, ds \qquad \sqrt{sx} = z \\ &= c_o \exp(-z^2/x)\ \Sigma(z^{2n}/\Gamma_{n+1}\Gamma_{n+1-p}) \int_{(1/x)\,(A/h)^{2+\alpha-\beta}}^{(1/x)\,(B/h)^{2+\alpha-\beta}} e^{-s}\, s^{n-p}\, ds \end{aligned}\right\} \quad \ldots\ldots (27)$$

The ground concentrations are obtained from (18) as

$$\left.\begin{aligned} c_{z=o}(x) &= (C_o/\Gamma_{1-p}) \int_{(1/x)\,(A/h)^{2+\alpha-\beta}}^{(1/x)\,(B/h)^{2+\alpha-\beta}} e^{-s}\, s^{-p}\, ds \\ &= [(1+\alpha)h^{1+\alpha}/(B^{1+\alpha} - A^{1+\alpha})] \left\{ I(s_B - p) - I(s_A - p) \right\} \\ s_y &= (1/x)\,(y/h)^{2+\alpha-\beta}\,(1/\sqrt{1-p}) \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (28)$$

where I(s, u) is the PEARSON [1946] notation for the incomplete gamma function and is defined as

$$I(s,u) = \int_0^{s\sqrt{1+u}} \exp(-s)\, s^u\, ds/\sqrt{(1+u)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (29)$$

For a line source located at h we obtain the following concentrations by taking the limits of (27) and (28) as $A \rightarrow h \leftarrow B$

$$c(x,z) = [(2+\alpha-\beta)/x]\, z^p\, e^{-(z^2+1)/x}\, I_{-p}(2z/x) \quad \ldots\ldots\ldots\ldots\ldots\ldots (30)$$

$$c_{z=o}(x) = [(2+\alpha-\beta)/\Gamma_{1-p}]\, e^{-1/x}\, x^{p-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots (31)$$

Differentiating (31) we obtain for the point of maximum concentration

$$x_m = 1/(1-p) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (32)$$

and for the value of the maximum concentration

$$c_m = [(2+\alpha-\beta)/\Gamma_{1-p}][(1-p)/e]^{1-p} \quad \ldots\ldots\ldots\ldots\ldots\ldots (33)$$

Defining new variables, x′ and c′ as

$$\left.\begin{aligned} x' &= X/X_m = x/x_m \\ c' &= C/C_m = c/c_m \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (34)$$

We may re-express (31) as

$$c'(x') = [e^{1-1/x'}/x']^{1-p} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (35)$$

This form of the ground concentration is most suitable for graphical presentation. For comparison purposes some of the non-standard source problems will be presented in the x′, c′ notation where x_m and c_m are the maximum values for the standard, elevated line source.

Figure 2 relates c_m and x_m as functions of β and Z_1/Z_o according to the wind profile fit of (11) where $Z_1 = \ell = h$, the height of the source. Similarly, Figure 3 gives 1-p as a function of β and Z_1/Z_o. Figure 4 is then a graph of $c'_{z=o}(x')$ for various values of 1-p.

Figure 1 is a graph of the down-wind concentrations from the area source considered above where the width of the source is 0.1h. x′ and c′ are given as multiples of the maximum values for the line source, and in both Figures 1 and 4 the value of Z_1 was taken as the height of the source. For comparison, the down-wind concentrations from a line source are included in Figure 1.

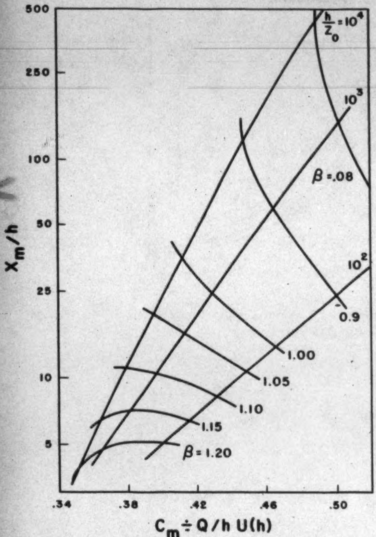

Fig. 2--Maximum ground concentration and point of maximum concentration as a function of β and h/z_o for line source and wind profile fitted to $Z_1 = h$

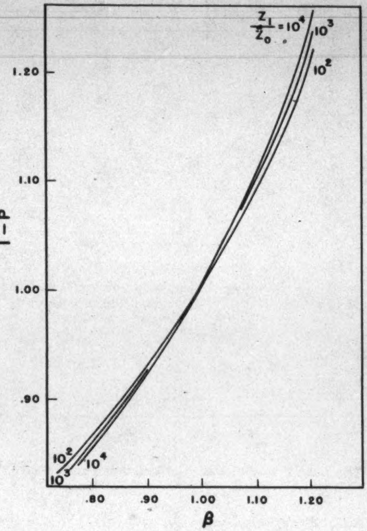

Fig. 3--1-p as a function of β and Z_1/Z_o

Triangular source--Let the source conditions be given as

$$F(Z) = \left.\begin{array}{ll} C_oZ/\phi A & 0 \leq Z \leq \phi A \\ = (A - Z)\,C_o/(1 - \phi)\,A & \phi A \leq Z \leq A \\ = 0 \qquad \text{elsewhere} & \end{array}\right\} \qquad (36)$$

or graphically as in Figure 5.

We assume that A, ϕ, and Q are given, and again determine C_o from the continuity condition obtaining

$$C_o = Q/\left\{\int_0^{\phi A} v_* qZ^{\alpha}Z_o^{-\alpha}Z(\phi A)^{-1}\,dZ + \int_{\phi A}^{A} v_* q(A - Z)\,Z^{\alpha}Z_o^{-\alpha}[(1 - \phi)\,A]^{-1}\,dZ\right\}$$

$$= [Q(1 - \phi)/A\,U(A)]\left\{(2 + \alpha)(1 + \alpha)/(1 - \phi^{1+\alpha})\right\} \qquad (37)$$

Setting ℓ equal to A in the transforms of (12), we then have

$$c_o = (2 + \alpha)(1 + \alpha)(1 - \phi)/(1 - \phi^{1+\alpha}) \qquad (38)$$

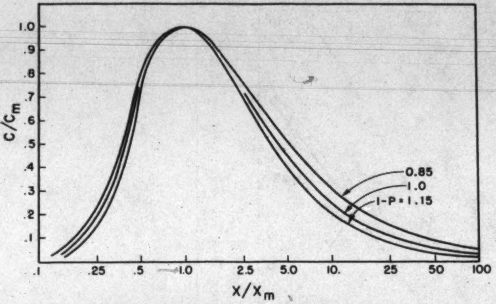

Fig. 4--Down-wind concentration for range of 1-p; values of concentration and distance in units of maxima for 1-p = 1

and

$$\left.\begin{aligned} f(z) &= (C_o/\phi)\, z^{2/(2+\alpha-\beta)} && 0 \leq z \leq \phi^{(2+\alpha-\beta)/2} \\ &= [C_o/(1-\phi)][1 - z^{2/(2+\alpha-\beta)}] && \phi^{(2+\alpha-\beta)/2} \leq z \leq 1 \\ &= 0 \qquad \text{elsewhere} && \end{aligned}\right\} \dots\dots\dots \quad (39)$$

The required solution for the ground concentration is then given by (18) and (19) as

$$c_{z=o}(x) = b_o(x)/\Gamma_{1-p} = \int_o^{\infty} [f(\sqrt{sx})/\Gamma_{1-p}]\, e^{-s}\, s^{-p}\, ds$$

$$= (C_o/\Gamma_{1-p}) \Big\{ x^{1/(2+\alpha-\beta)} \Big[\int_o^{\frac{\phi}{x}^{2+\alpha-\beta}} \frac{e^{-s}\, s^{1/(2+\alpha-\beta)-p}}{\phi}\, ds - \int_{\phi/x}^{1/x} {}^{2+\alpha-\beta} \frac{e^{-s}\, s^{1/(2+\alpha-\beta)-p}}{1-\phi}$$

$$+ \int_{\frac{\phi}{x}^{2+\alpha-\beta}}^{1/x} \frac{e^{-s}\, s^{-p}}{1-\phi}\, ds \Big\} = [C_o/(1-\phi)] \Big\{ I(s_1\, u_1) - I(s_2, u_1)$$

$$+ (\Gamma_{1+u_2}/\Gamma_{1+u_1}) \Big[\frac{x^{1/(2+\alpha-\beta)}}{\phi} I(s_3, u_2) - x^{1/(2+\alpha-\beta)}\, I(s_4, u_2) \Big] \Big\} \quad \dots\dots\dots\dots \quad (40)$$

where

$u_1 = -p$
$u_2 = -p + 1/(2 + \alpha - \beta)$
$s_1 = 1/x(1 + u_1)^{1/2}$
$s_2 = \phi^{2+\alpha-\beta}/x(1 + u_1)^{1/2}$
$s_3 = \phi^{2+\alpha-\beta}/x(1 + u_2)^{1/2}$
$s_4 = 1/x(1 + u_2)^{1/2}$

and $I(s, u)$ is again the Pearson notation for the incomplete gamma function.

Figure 5 is a graph of this solution for the particular case $\beta = 1$. $Z_1/Z_o = 10^3$, and $\phi = 0.7$. For comparison, the ground concentration from line sources at the ground and at a height A are included. In all three cases Z_1 was taken equal to 5A.

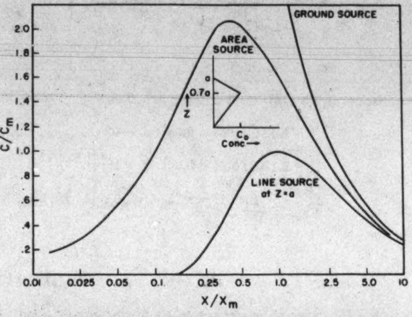

Fig. 5--Ground concentration for area source (see inset), and line sources at $z = a$ and $z = 0$; $\beta = 1$, $a/z_0 = 2 \times 10^2$, wind profile fitted to $z_1 = 5a$; concentration and distance in units of line source maxima [0.428 $Q/a\,U(a)$ and 19.3a]

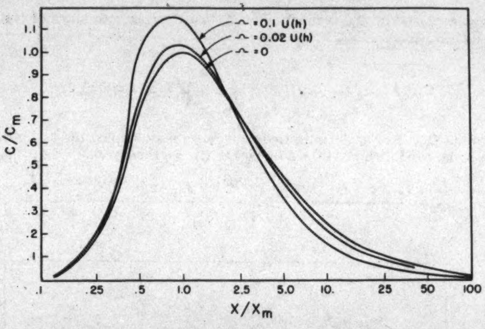

Fig. 6--Down-wind concentration for range of free fall velocities; concentration and distance are in units of zero fall-velocity maxima; line source, $\beta = 1$, $h/z_0 = 10^3$, wind profile fitted to $z_1 = h$

Fall velocity

As was pointed out under general solutions, the free fall velocity problem under adiabatic conditions reduces to the zero free fall velocity solution with p replaced by ω. For comparison, Figure 6 gives the down-wind concentrations from a line source located at h for $\Omega = 0$, -0.02, and -0.1 times the mean wind speed at h. We have taken Z_1 equal to h, and $h/Z_0 = 10^3$.

Inversion conditions

The base of an elevated inversion layer tends to act as a lid on the upward diffusion of matter. Such elevated inversion layers are associated with subsidence and frontal phenomena and with the early morning break-up of the nocturnal inversion. Normally, neutral or slightly unstable conditions prevail below the inversion. A rough mathematical model of these conditions may be constructed by imposing the condition that the flux, $-K(\partial C/\partial Z)$, at the base of the inversion, $Z = H$, be zero, while the stability and wind profile below the inversion are arbitrary. The solution is then obtained from (14) where the transforms of (12) were made as

$$\left.\begin{aligned} x &= (2+\alpha-\beta)^2\, K(H)\, X/H^2\, U(H) \\ z &= (Z/H)^{(2+\alpha-\beta)/2} \\ c &= C\, h\, U(h)/Q \end{aligned}\right\} \qquad (41)$$

The boundary conditions which (14) must satisfy are then

$$-K(\partial C/\partial Z) = 0 \text{ at } Z = 0 \qquad (42a)$$

$$-K(\partial C/\partial Z) = 0 \text{ at } Z = H \qquad (42b)$$

$$\lim_{X \to 0} C = F(Z) \qquad (42c)$$

The solution is thus

$$c = z^p\,[c_1 J_p(\sigma z) + c_2 J_{-p}(\sigma z)]\, \exp(-\sigma^2 x/4) \qquad (43)$$

where the constants c_1, c_2, and σ must be chosen to fit the boundary conditions. Condition (42a) determines c_1 as zero; (42b) determines σ as a root of $J_{1-p}(x)$ or zero.

The third boundary condition may be re-expressed as

$$C_\sigma x^p\, J_{-p}(\sigma z) = f(z) \qquad (44)$$

where c_2 has been replaced by C_σ, a function of σ. Multiplying both sides of (44) by $z^{1-p}\, J_{-p}(\sigma z)$ and integrating dz we have

$$C_\sigma \int_0^1 z\,[J_{-p}(\sigma z)]^2\, dz = \int_0^1 z^{1-p} f(z)\, J_{-p}(\sigma z)\, dz \qquad (45)$$

which will determine C_σ. For an infinite line source we may employ the same limiting technique as before on the right-hand side of (45). Solving for C_σ we then have

$$C_\sigma = \frac{(2+\alpha-\beta)\,(h/H)^{(3+2\alpha-\beta)/2}\, J_{-p}[\sigma(h/H)^{(2+\alpha-\beta)/2}]}{[J_{-p}(\sigma)]^2} \qquad (46)$$

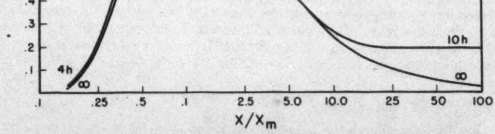

Fig. 7--Down-wind concentration for range of inversion heights; concentration and distance are in units of ∞ inversion maxima; $\beta = 1.0$, $h/z_0 = 10^3$, wind profile fitted to $z_1 = h$

and thus the complete solution is

$$c = (2 + \alpha - \beta)\,(h/H)^{(3+2\alpha-\beta)/2}\,z^{p} \sum_{j=0}^{\infty} \frac{J_{-p}(\sigma_j z)\,J_{-p}[\sigma_j (h/H)^{(2+\alpha-\beta)/2}]\,e^{-(\sigma_j{}^2 x/4)}}{[J_{-p}(\sigma_j)]^2} \quad \ldots (47)$$

where σ_j is the jth root of $J_{1-p}(x)$ and $\sigma_o = 0$.

To obtain ground concentrations we take the limit of (47) as z → 0 obtaining

$$c_{z=o}(x) = (2 + \alpha - \beta)/\Gamma_{1-p})\,(h/H)^{(3+2\alpha-\beta)/2} \sum \frac{(\sigma_j/2)^{-p}\,J_{-p}[\sigma_j (h/H)^{(2+\alpha-\beta)/2}]\,e^{-\sigma_j{}^2 x/4}}{[J_{-p}(\sigma_j)]^2} \quad \ldots\ldots\ldots\ldots (48)$$

This series is rapidly convergent for reasonably large values of x, and does not present a very great calculation problem. Figure 7 gives down-wind concentrations for the base of the inversion at H = 4h and 10h. For comparison, the ground concentrations for inversion $Z = \infty$ from (31) are also presented. The concentration and down-wind distances are given in units of the maximum values for the infinite inversion case.

Acknowledgments

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MICROSALINOMETER FOR OCEANOGRAPHIC MODEL STUDIES

John H. Lincoln, Robert G. Paquette, and Maurice Rattray, Jr.

(Contribution No. 183 from the Department of Oceanography of the University of Washington)

Abstract--An instrument has been developed for determining salinity structure in a small-scale oceanographic model of Puget Sound. Variations in electrical conductivity with depth at any point in the model are measured with a small probing conductivity cell. The conductivity-depth diagram is traced by an oscilloscope and photographed. Response to changes in conductivity is about 0.05 sec. The present accuracy of measurement is about one per cent. With suitable modifications the instrument may be adapted to a model of almost any scale. Adaptation to use for rapid salinity determination of sea water samples where titration accuracy is not required has been suggested.

Introduction--An oceanographic model has been constructed at the Department of Oceanography, University of Washington [BARNES, LINCOLN, and RATTRAY, 1954], as an aid in studying the structure and movement of the waters of Puget Sound. The horizontal and vertical scales selected were 1.84 inches/naut mi (1/40,000) and 1/16 inch/fathom (1/1152), respectively. This resulted in a time scale of 3.055 sec/hr from the Froude model laws.

Of primary importance in the oceanography of Puget Sound is the salinity structure resulting from the mixing of salt water from the Pacific Ocean with local river runoff. To study this structure in the model, it was necessary to devise an instrument for determining, quickly and reliably, the salt concentration at all depths at selected locations. The small model scales used required that the instrument be able to resolve and record significant variations in salt concentrations within very small increments of depth with minimum disturbance of the water structure.

Methods investigated for determining the salinity structure in the model include the photometric determination of the concentration of a dye added in known ratio in either the river water or the salt water and the use of a Ag-AgCl concentration cell. The former was rejected because of the bulkiness of the sensing element and poor depth discrimination, and the latter because of the instability of the cell. The method finally adopted is based upon the conductivity of the water.

Construction--The salinity-indicating instrument, as constructed, is essentially a probing conductivity cell coupled to an oscilloscope. Water is drawn through the cell during the probing cycle, and a curve closely approximating a plot of conductivity versus depth is traced on the cathode-ray tube. The curve traced on the downstroke of the probe and a zero-conductivity trace produced on the return are photographed for a permanent record.

A number of cell designs were tried. Two-electrode cells are unsuitable because the outflowing salt water provides a leakage path to ground in parallel with the cell. This difficulty is eliminated by a symmetrical three-electrode cell with outer electrodes grounded. The final design is shown in Figure 1. The electrodes were made from 1/8-inch silver alloy wire (Easy Flo silver solder) and drilled longitudinally with a no. 72 drill (0.025 inch). Copper leads were then soldered to each electrode. Holes were drilled in each end of two one-inch lengths of 1/4-inch Lucite rod to receive the electrodes. After the electrodes had been pressed into position in the plastic sections, the capillaries were drilled between them, thereby insuring perfect alignment. After cementing the two halves together, the cell was attached to a length of 1/4-inch plastic tube which acts as a support and through which the water is aspirated. The tubing was grooved on the outside to permit the leads from the electrodes to be imbedded in the plastic for insulation.

The probe is lowered and raised by an air cylinder controlled by a reversing valve. For each sampling cycle, the valve is actuated manually to start the cell lowering. When a preset depth is reached, reversal is automatic, and the cell is raised until it is out of the water. Operating speed is controlled by a needle valve in the air supply. A simplified drawing of the mechanism is shown in Figure 2. The assembly of cell and probing mechanism is easily portable over the model surface (about 10 × 20 ft).

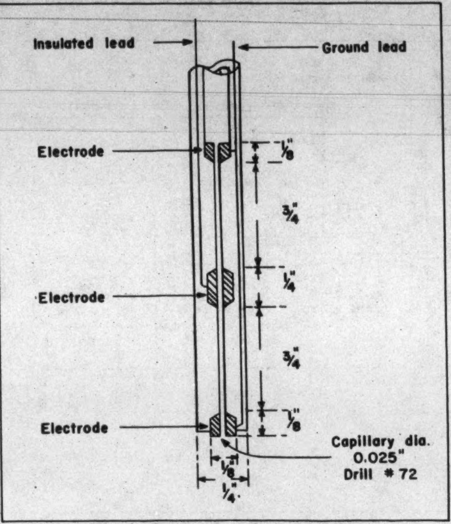
Insulated lead
Ground lead
Electrode
Electrode
Electrode
1/8"
3/4"
1/4"
3/4"
1/8"
Capillary dia.
0.025"
Drill # 72
1/8"
1/4"

Fig. 1--Design of conductivity cell

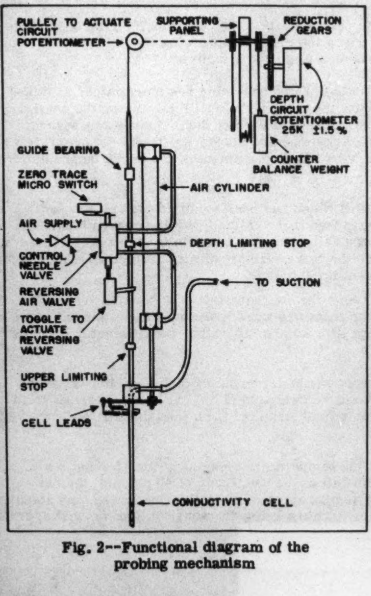
PULLEY TO ACTUATE CIRCUIT POTENTIOMETER
SUPPORTING PANEL
REDUCTION GEARS
DEPTH CIRCUIT POTENTIOMETER 25K ±1.5 %
COUNTER BALANCE WEIGHT
GUIDE BEARING
ZERO TRACE MICRO SWITCH
AIR CYLINDER
AIR SUPPLY
DEPTH LIMITING STOP
CONTROL NEEDLE VALVE
TO SUCTION
REVERSING AIR VALVE
TOGGLE TO ACTUATE REVERSING VALVE
UPPER LIMITING STOP
CELL LEADS
CONDUCTIVITY CELL

Fig. 2--Functional diagram of the probing mechanism

Measurement of the cell conductance could have been accomplished by determining the unbalance voltage of a Wheatstone bridge. However, it is sufficiently accurate to measure the electrical current flowing through the cell directly. The electrical circuits of the instrument embody some principles not ordinarily used in conductivity measurements. A schematic diagram is shown in Figure 3.

The oscillator consits of a twin triode as oscillator-amplifier [American Radio Relay League, 1951] followed by a 6V6 tube and transformer output. It supplies current to the conductivity cell at a frequency of 10,000 cycles and potentials adjustable up to 19 v. Regulation of the output is achieved by means of voltage regulation in the plate supply of the oscillator which, coupled with the low impedance of the output transformer, provides a sufficiently stable voltage source. The current is determined from the voltage drop across a precision 47-ohm resistor in series with the cell. This voltage is then amplified by a single stage RC amplifier and rectified by an infinite impedance detector having an additional filter network in the output circuit. The detector output is applied to the X-axis of the oscilloscope.

A potential divider in the power supply and a precision linear potentiometer actuated by the raising and lowering mechanism of the probe provide a DC voltage which varies with the vertical position of the probe. This voltage is applied to the Y-axis

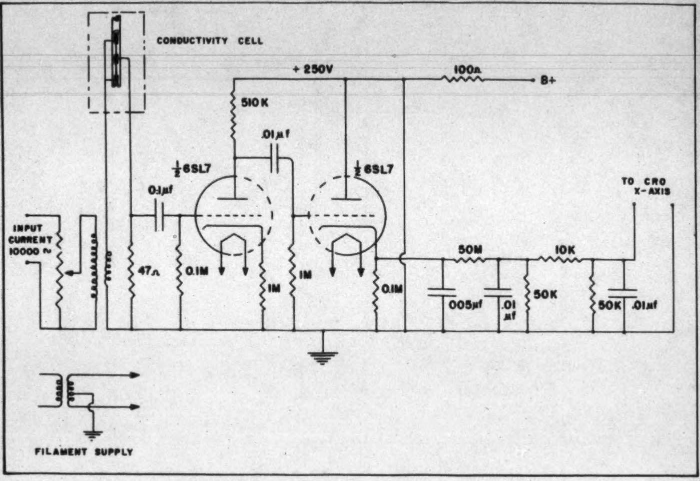

Fig. 3--Schematic diagram of the amplifier-detector circuit

of the oscilloscope; thus a plot of output voltage versus depth is produced on the face of the tube. A switch, actuated by the reversing air valve, opens the cell circuit during the upward travel of the probe to provide a reference trace corresponding to zero conductivity.

To facilitate adjustment of the instrument, a calibrated precision resistor may be switched into the cell position in the circuit. This permits the gain on the oscillator and on the oscilloscope to be adjusted to produce a standard deflection. Operation of the instrument in several salinity ranges is possible by different choices of resistor and standard deflection. Accurately-machined blocks provide a means of controlling vertical displacement of the probe mechanism for direct calibration of the depth scale.

The oscilloscope used is a Dumont type 304-H which has been modified for use with a flat-faced tube since marked curvature of the photographed trace existed with the conventional tube. The DC amplifiers show a noticeable drift in zero deflection, but the gain is stable within the error of reading over a period of at least a day. Since the line corresponding to zero conductance appears on each trace, a ready reference exists to correct for the drift.

Sensitivity and accuracy--In order to determine the characteristics of the cell for conductivity measurements, cell resistances with known solutions were compared to calibrated wire-wound resistors using a Leeds and Northrup type K precision laboratory potentiometer in place of the oscilloscope.

A typical cell constant, determined from seven sea water samples of known chlorinity and temperature, was found to be 177.9 cm with a standard deviation of 0.5 cm in the Cl range 15 to 16^{o}/oo. The specific conductivity of the samples was determined from the tables given by THOMAS, THOMPSON, and UTTERBACK [1934].

The current density in the cell is such that the temperature rises at a rate of about 0.6°C per second; but when water is drawn through the cell at the usual rate of 40 cc/min, the cell volume is replaced in 0.028 sec and the average temperature in the cell is increased only about 0.008°C. Temperature changes of this amount or less are below the sensitivity of normal operation.

Probing action--The effect of the probing action of the conductivity cell on the structure of the water was studied by visual observations of its travel through a sharp interface of a two-layer fresh- and salt-water system. The disturbance of the two-layer system was made visible as shadows on ground glass caused by the differential refraction of transmitted parallel light, somewhat similar to the Schlieren method. The image on the ground glass was photographed for close examination (Fig. 4).

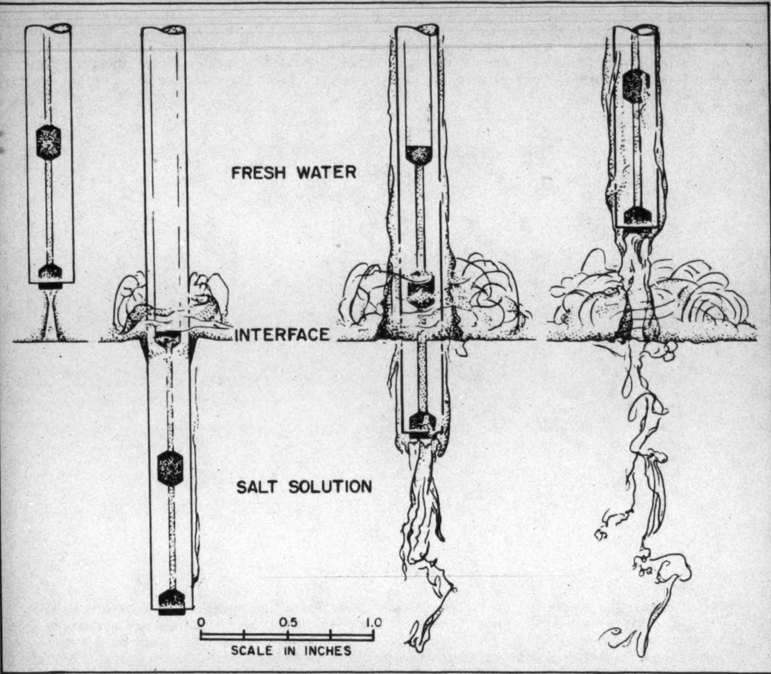

Fig. 4--Tracings from photographs of the probe action at a sharp interface (left to right: probe approaching interface, tiny vortex visible; probe descending past interface; probe ascending, tip below interface; probe ascending, tip above interface)

Under normal operating conditions, passage of the probe through the system appears to cause no significant disturbance at the cell tip during lowering. However, observations indicate that water is drawn into the cell in a vortex of very small diameter extending about 0.1 inch or less ahead of the tip.

The greatest mixing or disturbance of the system occurs from the surface drag or skin friction of the probe. During the downward travel through the interface, a thin skin of the upper layer is carried into the lower layer by the exterior of the probe. Since this mixed water tends to rise, it does not contaminate the water being drawn into the cell. Upon reversal of direction, the heavier water begins to be carried upward, sloughs off the probe, and sinks. Since water is being drawn into the cell continuously, most of the mixed water in both layers is removed. When the probe was observed operating without suction, the mixing was markedly increased.

Resolution of salinity structure--The resolution of salinity structure in the model depends upon the flushing time of the cell, the rate of lowering of the probe, and the effect of the tip vortex. The rate of response to a conductivity change is determined by the time necessary to flush the cell, which is calculated to be about 0.028 sec. During this time the probe travels about ten equivalent feet at the normal lowering rate of 3 to 4 inches/sec. Since the response of the cell is roughly proportional to the degree of flushing, an approximately linear averaging occurs over this depth range. Superimposed upon this is the effect of the tip vortex reaching downward and drawing a sample integrated over about a ten-foot range. Thus some integration takes place over about a 20-ft range. These two effects are somewhat compensating with respect to depth errors. Further compensating is the fact that the tip vortex is established, and the water surface is recorded even before the probe enters the water. Even an approximate theoretical treatment of these processes is not possible, and the reader is referred to Figure 6 and a following section for an experimental demonstration of the behavior under typical conditions.

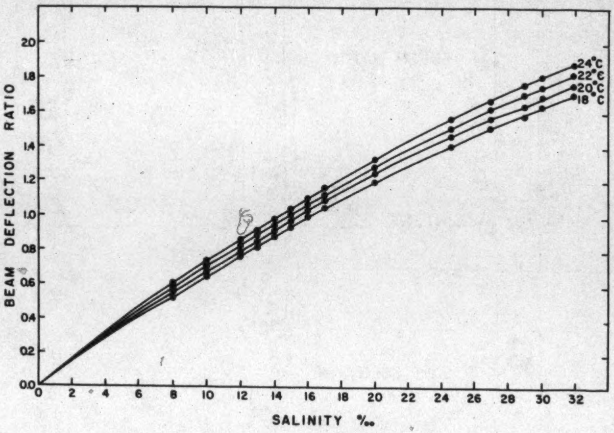

Fig. 5--Typical calibration curves

Calibration--It is desirable to be able to correlate directly the conductivity in terms of salinity to simplify the data obtained from the model. Since the temperature of the water in the model is controlled at approximately room temperature, the water is essentially isothermal in structure but may vary slightly from day to day. Temperature corrections for the calibration are therefore necessary. Calibration of the instrument consists in determining the ratio of beam deflection to standard deflection on the oscilloscope with the cell drawing standard salt solutions at known temperatures within the desired range.

A typical calibration curve plotted as deflection ratio versus salinity at constant temperature is shown in Figure 5. A recheck of the cell calibration after ten months of operation showed no change within the accuracy of the instrument.

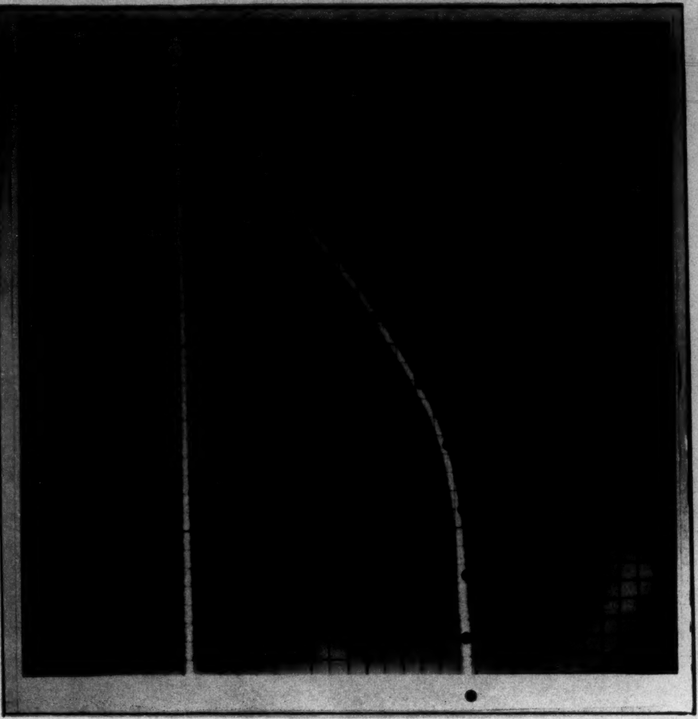

Fig. 6--Comparison of conductivity profiles determined by the microsalinometer (continuous trace) and by titration (black dots)

Verification--An additional test of the instrument was made which provided further evaluation under conditions closely resembling those encountered in normal use. In a small glass tank, a smooth gradient was established between a very dilute solution and salt water of a concentration approaching that of sea water. The conductivity profile was then determined in two independent ways. The probe was positioned over the tank and operated in the normal manner to obtain a profile. Small samples of about 1.5 ml were then carefully withdrawn at 15-mm intervals, from the surface to below probing depth, by means of a fine capillary pipet with horizontal tip. Finally, the gradient was again probed three times at 30-sec intervals and the temperature was measured at every 30 mm of depth.

The salt content of the samples was determined by titration using the Volhard method. The beam deflection of the oscilloscope corresponding to the salt content and temperature of the samples was computed from the calibration curve of the cell and the measured standard calibration deflection. These values, plotted on the photographic print of the oscilloscope trace, are shown in Figure 6.

It may be seen that good agreement was obtained by the two methods. The deviations appear to approximate the titration error due to the small size of the samples. Profiles taken before, and 30 and 60 sec after, drawing the 1.5 ml samples showed barely detectable differences, indicating that no significant disturbance of the gradient was caused by the probing action.

Acknowledgment--The authors wish to express their appreciation to Charles C. Andrew for his assistance in the design and construction of the oscillator-amplifier-detector unit. This work was supported in part by the Office of Naval Research under Contract No. N8onr-520/III with the University of Washington.

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A TECHNIQUE FOR THE SPECTRAL ANALYSIS OF SOUND IN THE OCEAN

Paul Ferris Smith, Joseph D. Richard, and Frank H. Stephens

(Contribution No. 143 from the Marine Laboratory, University of Miami.)

Abstract--A method is given for presenting a continuous quantitative spectrum of sound in the ocean. A more detailed spectrum is obtained than from previous methods with the advantage of convenient and rapid operation. The technique has proved useful in the analysis of subsurface oceanic sounds, examples of which are given, and will facilitate the analysis of oceanographic noise spectra of meteorological, biological, or volcanic origin. The method is based upon a modification and adaptation of a commercially-available heterodyne type sonic analyzer with cathode ray tube presentation. Provisions for photographic recording have been added.

Description of analyzer--By modifying a commercial sound analyzer designed primarily for visual qualitative production-line type use, a versatile quantitative recording analyzer for studying underwater oceanic sounds has been developed.

The modified analyzer, a Sonic Analyzer Model LP-1, manufactured by the Panoramic Radio Products Corporation, Mt. Vernon, N. Y., is a heterodyne type analyzer [BERANEK, 1949], the operation of which can be seen in the block diagram of Figure 1. Briefly, the tape-recorded acoustic signal, obtained from a hydrophone and recorder in the field, is amplified and mixed with a local oscillator (sweeping oscillator) the frequency of which sweeps from 80 to 99.96 kc. As components of the input signal beat with this local oscillator to produce a 100-kc sum frequency (or side band), they are passed through the 100-kc filters, amplified, rectified, and used to deflect the spot vertically on the cathode ray tube indicator. This frequency sweep is controlled by the sawtooth voltage generator which also controls in synchronism the horizontal position of the cathode ray tube spot. This results in an amplitude versus frequency pattern which can be photographed through engraved edge-lighted transparent grids. Controls allow the choice of a logarithmic frequency scale from 40 cps to 20 kc or linear frequency scales 100, 500, or 1500 cps wide. Similarly, the amplitude scale can be logarithmic (db) or linear (pct), but in acoustics the former has greater usefulness so the two transparent grids are engraved with this scale only.

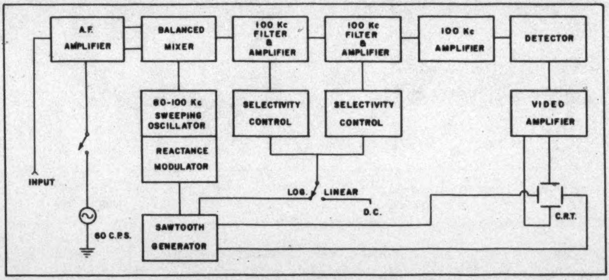

Fig. 1--Block diagram of sonic analyzer

Reproductions of several presentations are given in Figures 2 and 3 showing both logarithmic and linear frequency and amplitude scales.

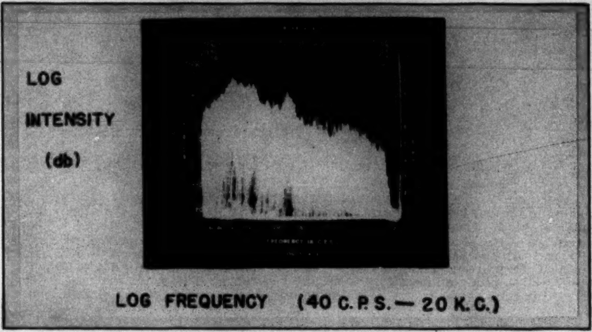

Fig. 2--Example of analyzer presentation; abscissa is logarithmic frequency scale and ordinate is logarithmic intensity scale

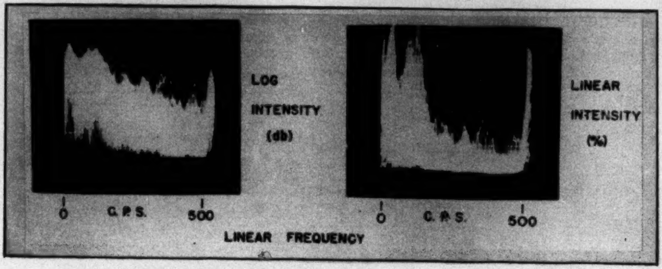

Fig. 3--Example of analyzer presentation with linear frequency scale (abscissa) and logarithmic and linear intensity scales (ordinate); the same noise is presented on both

Experimental procedure--Figure 4 shows the experimental procedure whereby underwater noise recordings are made and analyzed to obtain acoustic spectrum level curves. The concept spectrum level, or level in single cycle bands [BERANEK, 1949], is standardized for reducing wide-band noise measurement for intercomparison. In Figure 4a is shown the recording procedure. This system is used in the field on board the research vessel to record both the sound of interest and suitable calibration signals. Using a number of sinusoidal calibration signals of known amplitude and frequency, the response characteristics of the hydrophone, and the effective band widths of the analyzer 'filters' (and taking account of any changes of gain made during recording and analyzing), it is possible to compute the overall response of the system and therefrom the absolute acoustic spectrum level of the sound recorded in the field. It is possible to read the average maximum or minimum noise envelope, as well as the transient maxima from the analyzer photographs and to compute the spectrum level of each. In addition, corrections can be determined for the effective RMS noise spectrum level.

In Figure 4b is shown the step which transfers the portion of the field recording to be analyzed to an endless magnetic tape loop. The calibration signals are similarly transferred by re-recording.

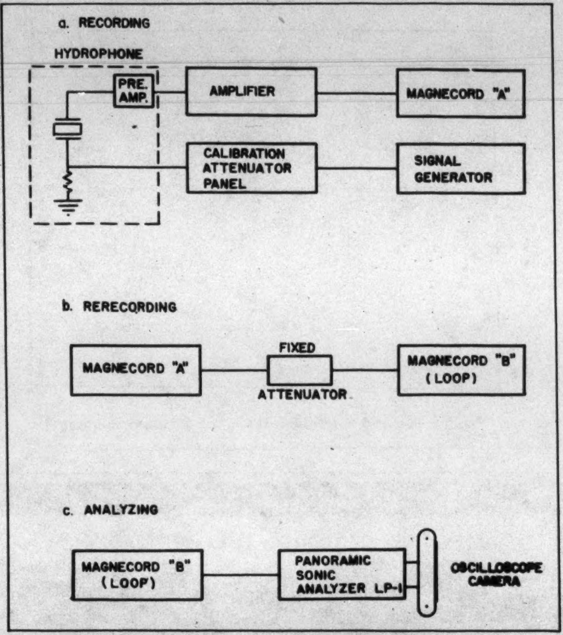
a. RECORDING
HYDROPHONE
PRE. AMP.
AMPLIFIER
MAGNECORD "A"
CALIBRATION ATTENUATOR PANEL
SIGNAL GENERATOR
b. RERECORDING
MAGNECORD "A"
FIXED
ATTENUATOR
MAGNECORD "B" (LOOP)
c. ANALYZING
MAGNECORD "B" (LOOP)
PANORAMIC SONIC ANALYZER LP-1
OSCILLOSCOPE CAMERA

Fig. 4--Block diagram of noise recording and analysis system

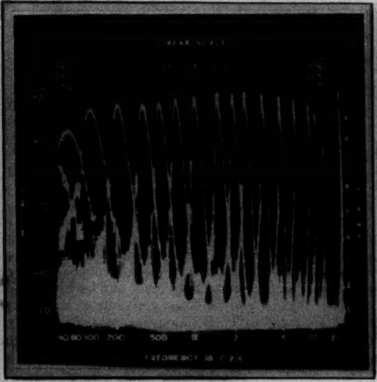

Fig. 5--Analysis of a calibration signal

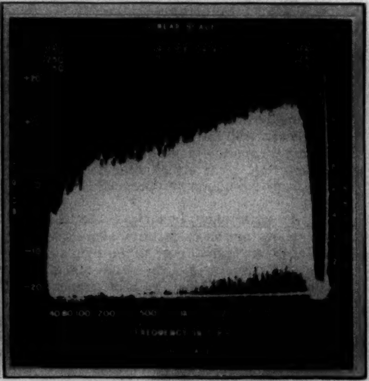

Fig. 6--Analysis of a noise signal

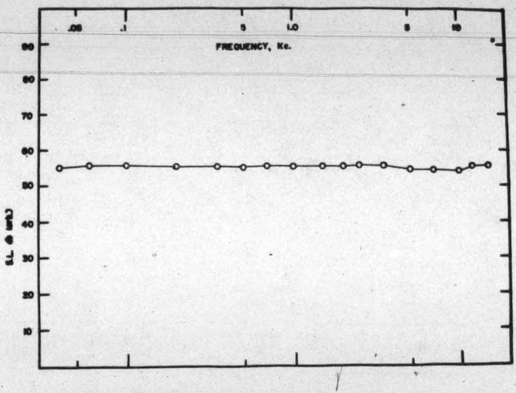

Fig. 7--Analyzed spectrum level output of noise generator

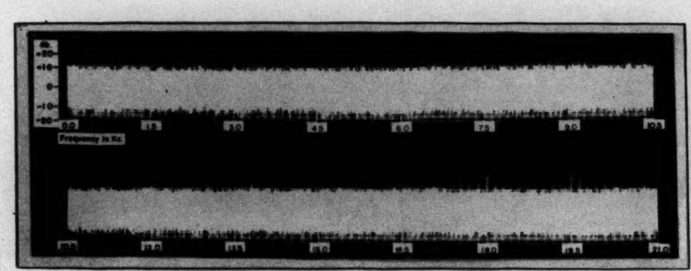

Fig. 8--Noise signal of Figures 6 and 7 analyzed directly

In Figure 4c the endless loop is played through the analyzer to give the type of result shown above in Figures 2 and 3. The adopted practice (having chosen a loop length so as to be slightly out of phase with the one-second analyzer sweep) is to let the analyzer sweep 90 times, thereby assuring a complete sampling of the recorded signal. However, by varying the exposure and playback duration, a variety of noise details can be investigated. These photographs are now read and the appropriate computations made.

An experimental example--To illustrate the use of this method, the output of an electronic noise generator and calibration signals have been recorded exactly as in the field procedure. These have then been transferred to the loop and analyzed. In Figures 5 and 6 are the oscilloscope photographs of the analysis of these two signals. From the sine wave signals the overall response curve is obtained. When these two photographs have been measured, the spectrum level can be computed and plotted. The final result is shown in Figure 7. That this is a white noise generator can readily be seen. This same noise signal is shown in Figure 8 analyzed directly using the linear frequency presentation of the analyzer. This was made by fitting together 14 analyzer photographs 1.5 kc wide and, because the effective bandwidth of the filters on linear presentation is constant, appears flat.

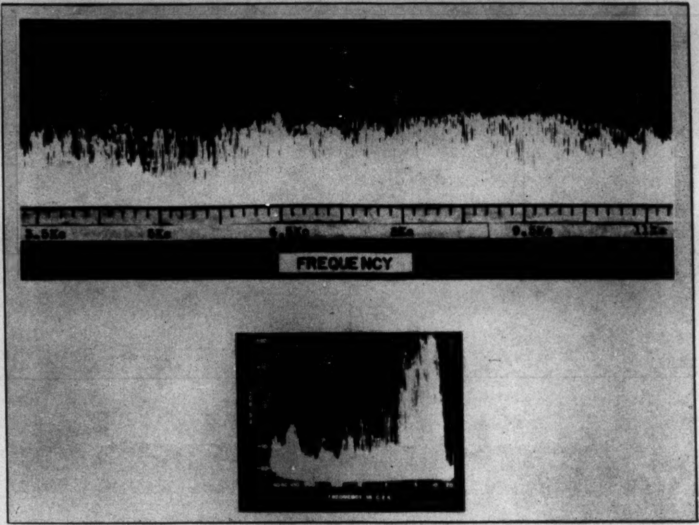

Fig. 9--Frequency components of a typical porpoise whistle; upper--composite 1500-cycle linear frequency scale; lower--logarithmic frequency scale; both--logarithmic intensity scales

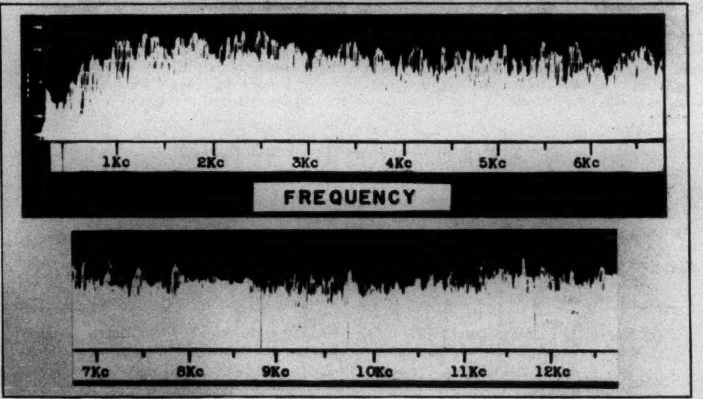

Fig. 10--Frequency components of shrimp snaps; composite linear frequency scale and logarithmic intensity scale

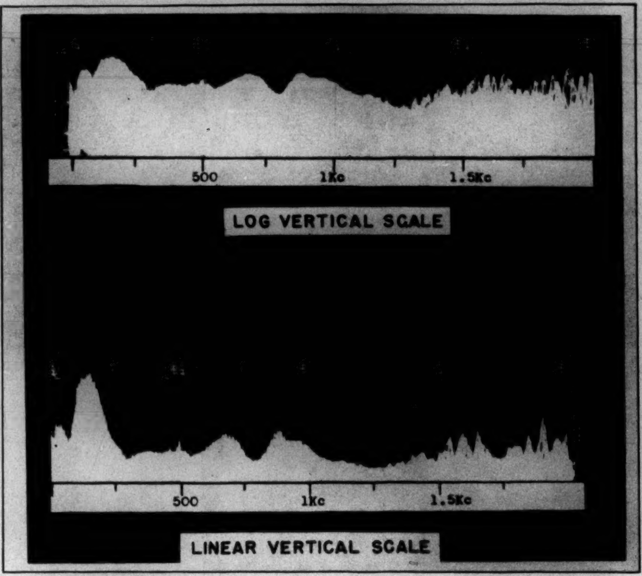

Fig. 11--Frequency components of queen trigger fish noise; composite linear frequency scales; upper--logarithmic intensity scale; lower--linear intensity scale

Further illustrative results--Figures 9 through 11 show the analyzer presentation of three oceanic noise signals of biological origin.

Summary--The advantages of this method are the relative ease of use and the detailed graphic presentations that can be read to give absolute values for average levels and transient maximum and minimum throughout the whole audio spectrum or over expanded selected portions of this spectrum.

Acknowledgment--These studies were aided by Contract NObsr 57146 between the U. S. Navy Bureau of Ships and the University of Miami.

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ON A HILLSIDE MOISTURE GRADIENT IN VOLCANIC ASH SOIL, NEW ZEALAND

Bessel D. van't Woudt

Abstract--Data on a moisture gradient in the surface soil on a slope of about 30° and about 50 ft long in a small valley are presented. Moisture increases more or less gradually from the top to the foot of the slope. Three factors seemed to contribute toward the establishment of this gradient: (1) an increase from the top to the bottom of the slope in the depth of soil wetted during a rain storm as a result of (a) surface- and sub-surface storm flow, and (b) incomplete wetting by rain of the surface soil on the upper half of the slope because of a resistance to wetting generally exhibited by the soil in this position; (2) an increase in moisture retention capacity of the soil with descent on the slope; and (3) decreasing evaporation from the soil surface with descent on the slope apparently because of decreased exposure to air currents.

Introduction--Experimental work on subsurface storm flow carried out on a slope of about 30° and about 50 ft long in volcanic ash soil in a small valley near Taupo was described by the author [VAN'T WOUDT, 1954]. Work has continued and this paper presents observations on the soil-moisture gradient on this slope whereby attention is being paid to the origin of this gradient.

The moisture gradient--Although other methods were attempted, most information has been obtained from the gravimetric determination of moisture content in soil samples collected on the occasion of visits to the area, for which figures are given in Table 1.

Table 1--Soil moisture on the experimental area

Date of sampling	Depth sampled	Position on slope					
		Flat beyond foot	Foot	Lower	Mid	Upper	Top
		Distance in feet from foot of slope					
		4-0	0-2	2-12	12-28	28-48	48-52
	inch	pct[a]	pct	pct	pct	pct	pct
1950							
Nov. 20	0 - 3	112.2	....	91.0	67.1	40.0	49.9
	0 - 3	110.6	....	94.9	58.0	46.7	48.0
	0 - 3	140.3	....	...	...	...	...
Nov. 22	0 - 6	106.2	....	71.3	61.2	43.0	48.7
	0 - 6	125.6	....	...	...	...	...
Nov. 23	0 - 6	68.8	....	78.8	62.5	46.2	40.0
1951							
Jan. 22	0 - 6	70.7	....	...	...	...	22.5
	0 - 6	....	....	...	...	...	31.4
Jan. 28	0 - 3	92.7	....	63.9	58.4	34.9	46.4
	0 - 3	79.2	....	61.4	63.4	53.4	43.6
Feb. 6-9	0 - 6	85.6	91.4	79.5	70.0	45.0	50.5
1953							
June 28	0 - 6	91.4	100.9	100.0	85.1	57.6	63.0
Aug. 24	0 - 6	140.0	....	71.3	68.5	64.0	43.5
	0 - 6	....	....	76.0	65.3	44.0	43.6
Nov. 15	0 - 8	91.6	81.2	83.2	62.4	52.7	42.9
		....	....	63.1	59.2	35.3	...
Average		101.1	91.2	77.9	65.1	46.9	44.2

[a] Moisture as a percentage of the weight of oven-dry soil.

The average values give an indication of prevalent moisture levels on the slope. It is seen that the soil moisture content at the top is about half that at the foot of the slope, with intermediate values between. The moisture content on the upper half of the slope (above 28 ft - Table 1) would have been somewhat higher if it were expressed on a volume-basis because of an overall higher specific gravity of the soil particles here (specific gravity 2.30 on the upper half compared with 2.15 on the lower half of the slope), related to a greater admixture with andesitic particles. (Similar low specific gravities have been measured for other soil types derived from volcanic ash in neighboring country).

Table 2--Relationship between earth resistivity and soil moisture as a percentage of the oven-dry weight of soil

mV	mA	$\frac{mV}{mA}$	log $(\frac{mV}{mA})$	Moisture	log moisture
				pct	pct
400	0.45	890	2.95	91.6	1.96
500	0.46	1090	3.04	81.2	1.91
500	0.37	1350	3.13	83.2	1.92
600	0.32	1880	3.27	63.1	1.80
500	0.30	1670	3.22	62.4	1.80
500	0.22	2270	3.36	59.2	1.77
500	0.20	2500	3.40	52.7	1.72
500	0.11	4550	3.66	42.9	1.63
500	0.07	7140	3.85	35.3	1.55

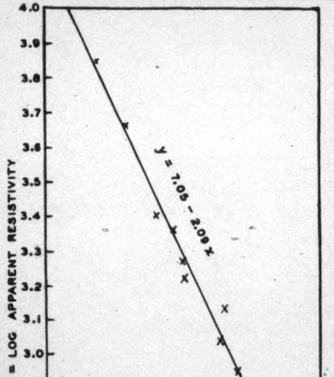

Fig. 1--Relationship between log apparent resistivity and log percentage moisture

The gradient from place to place along the slope is indicated by measurements made with an earth resistivity meter. This meter comprises the standard Gish-Rooney arrangement and the Wenner electrode configuration [HEILAND, 1940, p. 640]. For electrodes, copper screws were put through the center of small, round Perspex discs, 3/8 inch thick. The pointed end, to be pushed into the soil, protruded half an inch. At this end the screw was filed smooth. Insulated wire interconnected the four electrodes (two current and two potential electrodes, the current electrodes being placed on the outside), which gave a fixed spacing of eight inches between the electrodes, a spacing used throughout these tests. In all measurements the electrodes were placed across the slope, after removal of litter, ensuring an even depth of penetration. The assumption has been made that the depth of soil over which the resistivity was measured is equal to the electrode spacing (eight inches) (HEILAND, 1940, p. 643).

The only significant variable assumed in the measurements is that of the position of the soil on the slope so that the measured or apparent resistivity (the true resistivity is obtained by multiplying the reading by a commutator factor) has been plotted immediately against soil-moisture content. Soil samples from the zero-to-eight-inch-layer were taken between the electrodes at the time resistivity was measured for calibration against soil moisture. These measurements are shown in Table 2 and Figure 1.

The resistivity measurements taken on two consecutive days in November 1951, with 0.28 inches of rain between the first and the second measurement (Table 3), were calculated as moisture as a percentage of the weight of oven-dry soil on the basis of the regression

Table 3--Earth resistivity and its estimated equivalent in soil moisture as a percentage of the weight of oven-dry soil

Distance in feet from foot of slope	November 8, 1950				November 9, 1950			
	mV	mA	$\frac{mV}{mA}$	Equiv. moist.	mV	mA	$\frac{mV}{mA}$	Equiv. moist.
				pct				pct
6	1000	0.98	1020	85	1000	1.6	625	110
4	1000	0.98	1020	85	750	1.95	385	137
2	550	0.85	650	107	680	1.6	425	130
Foot	700	1.4	500	120	840	2.3	365	140
2	775	1.8	430	129	800	2.2	365	140
4	870	0.91	960	89	820	1.5	550	116
6	500	0.57	875	93	900	0.90	1000	87
8	880	0.82	1070	83	800	0.78	1030	86
10	1000	0.84	1190	80	1000	0.80	1250	78
12	750	0.66	1140	81	830	0.67	1240	79
14	1000	0.76	1320	76	950	0.75	1270	78
16	1000	0.60	1670	68	900	0.65	1380	74
18	880	0.46	1910	64	1000	0.60	1670	68
20	880	0.46	1910	64	1000	0.49	2040	62
22	1000	0.67	1490	72	750	0.42	1790	66
24	500	0.35	1430	74	1000	0.63	1590	70
26	700	0.56	1250	78	1000	0.72	1390	74
28	950	0.75	1270	78	1000	0.58	1720	68
30	1000	0.60	1670	68	1000	0.50	2000	63
32	900	0.36	2500	56	1000	0.22	4550	43
34	900	0.36	2500	56	800	0.21	3810	47
36	600	0.10	6000	38	1000	0.22	4550	43
38	700	0.26	2690	55	1000	0.28	3570	48
40	800	0.24	3330	49	1000	0.50	2000	63
42	800	0.34	2350	59	900	0.42	2140	61
44	1000	0.30	3330	50	1000	0.35	2860	53
46	1000	0.24	4170	45	1000	0.16	6250	37
48	700	0.09	7780	33	1000	0.10	10000	30

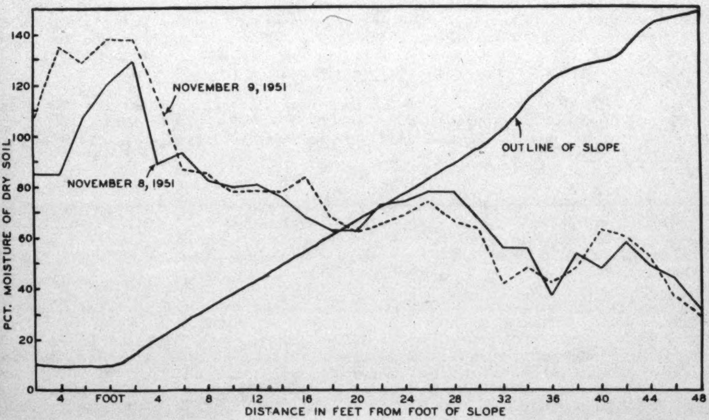

Fig. 2--Moisture gradient in the surface soil as deduced from earth resistivity measurements line in Figure 1 and are shown in Figure 2; this figure gives also the outline of the slope at the site of measurement.

As is seen from Table 3 the calculated moisture content at the foot of the slope is higher than that generally measured by gravimetric determination. A higher conductivity of the soil in this situation could be expected, but as soil sampling for calibration was carried out all along the slope any effect of varying conductivity is not considered large.

The data indicate that the moisture more or less gradually increases from the top to the foot of the slope. They also indicate that moisture was substantially increased near the foot of the slope following 0.28 inches of rain.

The origin of the moisture gradient--Although no systematic records of moisture gradients on sloping ground have come to the notice of the writer, the existence of such a gradient is often assumed in discussions. Under field conditions one can often observe an increasing verdure from the top to the bottom of sloping pastures after a dry summer spell which, according to measurement made at the Rukuhia Soil Research Station, is related to an increase in soil moisture content in the top soil in that direction. An attempt was made in this study to define factors giving rise to the moisture gradient on the experimental slope near Taupo. The following three factors seem to have a bearing on the problem.

Moisture repletion by rain--A small amount of surface storm flow was measured to originate on the upper half of the slope. This flow was caused by (1) a resistance to wetting generally exhibited by the surface soil, and (2) exposure of the soil surface on some of the steepest faces. In the latter case the surface becomes rather impervious by the effect of impact and splashing of rain drops. These two causes were absent on the lower half of the slope where the soil did not dry out sufficiently for resistance to wetting to become a factor of significance and where the soil surface was well protected by a moss cover. The infiltration rate of this soil is so high that virtually all surface storm water filters into the soil on reaching lower levels of the slope.

Surface storm flow thus reduces water supply from rain to the soil on the upper half of the slope and increases it on the lower half. Subsurface storm flow (dealt with in some detail for this slope by VAN'T WOUDT [1954]) has a similar effect.

Resistance to wetting, apart from causing surface storm flow, also affects wetting of the surface soil by rain. Applied water tends to filter into the subsoil through channels and along roots, leaving pockets of soil near the surface unwetted.

Moisture loss by drainage--In literature dealing with soil formation in relation to relief, the various positions on a slope are often classified to range from arid at the top to insufficiently drained at the foot of a slope. Intermediate between these two extreme situations the soil is often described as excessively- to well-drained on the upper half to soil with impeded drainage toward the foot. This particular slope is underlain by a great depth of porous material so that there is no effect of a water table on the variation in moisture content in the surface soil.

The moisture gradient on the slope is accompanied by a fertility gradient which has resulted from the down-wash of fine material [VAN'T WOUDT, 1952]. It was thus presumed that the moisture retention capacity of the surface soil increased down the slope with an increase in silt, clay and organic matter.

A determination of this value under field conditions is not possible, because when water is applied to the surface, pockets of soil near the surface may remain unwetted, as mentioned. A thorough wetting of the soil can be achieved, however, by allowing water to rise slowly from underneath, leaving the soil in contact with water for some time. On that basis a laboratory determinatio was made of possible differences in moisture retention capacity, using the apparatus shown in Figure 3.

Soil with undisturbed structure from the zero-to-six-inch layer was collected by tapping thin metal cylinders, six inches in diameter and six inches long, into the surface soil. The cylinder with soil was screwed onto stand (1) and the soil was saturated by applying water from a burette (2) till free water appeared at the surface. The soil was then left for 48 hours and additional water was added at the end of this period as required. The soil was then allowed to drain under gravity into the measuring cylinder (3) by opening and closing the taps (4) and (5). A lid (6) was then placed on the top, the junctions being made air-tight by using rubber rings (7). Suction was applied from a suction pump (8), the yalue being determined by an air-trap (9).

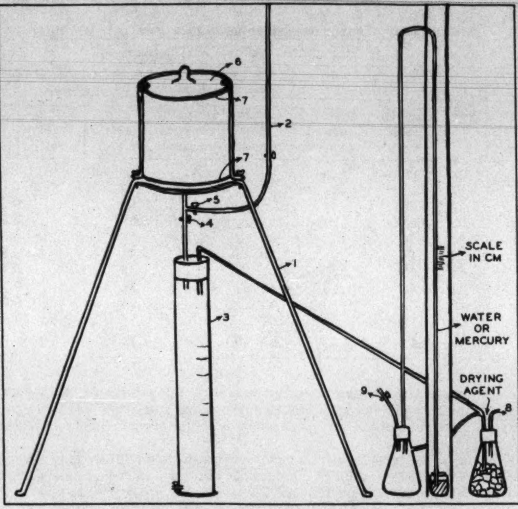

Fig. 3--Suction apparatus for determining field capacity

The average of two determinations made at arbitrary suction values, 100 cm and half an atmosphere, with this apparatus are shown in Table 4. The data have merely comparative value and as such they illustrate that more moisture was retained at a certain suction near the foot than higher up the slope. On this basis differences in moisture retention capacity seem to constitute a factor contributing toward establishing a moisture gradient in the surface soil on the slope.

Moisture loss by evaporation--The general incidence of resistance to wetting on the upper half of the slope (only effective at a moisture content approaching air-dry) and the general moisture level in the surface soil at this situation, led to the assumption that evaporation from the soil surface was considerably greater at higher than at lower levels on the slope. One way of checking on this possibility appeared to arise from comparing the yield of four comparable lysimeters, five inches in diameter and 11 inches long (see VAN'T WOUDT, [1954]), situated at four levels on the slope. The results are shown in Table 5.

The differences in yield are taken to reflect differences in moisture content of the soil in the lysimeters at the time of water repletion. Thus, at the top more water was required to produce outflow than at lower levels on the slope. The amount of rain taken up by the soil would then be due to different amounts of water lost by evaporation during the interval between rain storms. On that basis evaporation appeared to be about twice as large at the top as it was at the foot of the slope with intermediate values in between. The observations are of qualitative value only; they

Table 4--Moisture retention in the columns of soil

Approx. suction applied	Position on slope					
	Just beyond foot	Foot	Lower	Mid	Upper	Top
	pct[a]	pct	pct	pct	pct	pct
100 cm	117.5	106.2	98.5	96.0	84.7	67.6
1/2 atm	115.4	103.5	92.5	91.3	79.2	62.9

[a] Moisture as a percentage of the oven-dry weight of soil.

Table 5--Evaporation in relation to topographic position as deduced from lysimeter yield

Dates	Rainfall	Foot of slope			16 ft upslope			34 ft upslope			Top of slope (48 ft upslope)		
		Lysimeter yield		Deduced evaporation	Lysimeter yield		Deduced evaporation	Lysimeter yield		Deduced evaporation	Lysimeter yield		Deduced evaporation
	in	in	pct	in	in	pct	in	in	pct	in	in	pct	in
Nov. 11-12	1.05	0.33	...	...	0.39	...	...	0.02	...	...	0.02	...	...
Nov. 20	0.74	0.36	...	...	0.34	...	...	0.00	...	...	0.00	...	...
Nov. 21-22	0.65	0.63	...	...	0.48	...	...	0.36	...	...	0.23	...	...
Nov. 28-Dec. 17	1.38	0.14	...	...	0.00	...	...	0.00	...	...	0.00	...	...
Dec. 25-Jan. 3	5.13	3.77	...	...	2.29	...	...	1.24	...	...	0.89	...	...
Jan. 23-25	3.64	1.22	...	...	2.01	...	...	1.32	...	...	0.57	...	...
Jan. 26-27	0.64	0.47	...	...	0.42	...	...	0.31	...	...	0.13	...	...
Feb. 5-8	0.48	0.00	...	...	0.00	...	...	0.00	...	...	0.00	...	...
Feb. 9-10	1.50	1.52	...	...	1.67	...	...	0.72	...	...	0.13	...	...
Total	15.21	8.44	55.5	6.77	7.60	50.0	7.61	3.97	26.1	12.9	1.97	12.9	13.24

would not reflect actual evaporation taking place from undisturbed soil, as the water economy in the soil in the lysimeters differs from that in surrounding soil. They are taken to indicate differences in evaporative power of the air rather than of actual evaporation from the soil surface.

Such a conclusion is strengthened by observations made on differences in the evaporative power of the air in relation to relief in a somewhat similar situation, namely in a small valley in central Ohio, by WOLFE and Others [1943]. The evaporative power of the air at the valley bottom in that case was found to be only 11 to 31 pct of that measured at an exposed site, with intermediate values for in-between situations.

The sheltered position of the foot of the slope in the valley near Taupo (the valley floor is about 100 ft wide) and the rather strong winds, prevalent in the area, to which the upper part of the slope is exposed, are taken to account for differences in evaporation as are indicated by the lysimeter method. Differences in the evaporative power of the air apparently resulting from differences in exposure probably constitute a third factor which can help to explain the observed moisture gradient.

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DOES TRANSPIRATION DECREASE AS THE SOIL MOISTURE DECREASES?

F. J. Veihmeyer and A. H. Hendrickson

Abstract--This paper gives results obtained from a prune tree and from a pine tree grown in a suspended tank that permitted the obtaining of a continuous record of moisture loss from the soil. Additional results from field trials with pine, oak, and manzanita on a watershed area and from apricot and prune trees under cultivation show that the rate of moisture extraction from the soil is not influenced by the water in the soil so long as the latter is above the permanent wilting percentage.

The writers have answered this question in the negative a number of times by presenting data which show that water is readily available for transpiration between the limits of the field capacity and the permanent wilting percentage. A paper [VEIHMEYER and HENDRICKSON, 1948] which served as a report of the Committee on Physics of Soil Moisture for 1947, together with the discussion it invoked, dealt briefly with this question.

Recently in two papers dealing with watershed hydrology [KRAMER, 1952; LASSEN, LULL, and FRANK, 1952] the question is raised again and the conclusion drawn that at high moisture contents soil moisture will be reduced more rapidly than at lower moisture contents. Since the loss of moisture by direct evaporation from the soil surface is small compared to transpiration losses and is confined to a shallow surface layer of soil [VEIHMEYER, 1927; 1938], this statement can be taken to mean that it is believed that the rate of transpiration will be higher at high soil-moisture contents than at lower ones. It is the purpose of this report, therefore, to present data which show the relation between transpiration and soil moisture and to invite comments and discussion on this important question.

It is sometimes reasoned that because the tightness with which water is held by the soil increases as the soil-moisture content decreases, transpiration likewise must decrease. This, however, is not necessarily so when the soil-water-plant system as a whole is considered. The interpretation of soil moisture by means of energy changes was the subject of a report [VEIHMEYER and EDLEFSEN, 1937] for the year 1936-37 for the Committee on the Physics of Soil Moisture. EDLEFSEN [1941] in a report for this Committee for 1940-41 discusses the forces causing water to move through plants. The total free energy of the soil moisture surrounding the roots at the permanent wilting percentage is -0.16×10^8 ergs per gram. That of the air at 40 pct relative humidity and 30° is -12.8×10^8 ergs per gram giving an over-all drop in free energy from soil moisture to the air of -12.6×10^8 ergs per gram when the plant is under these specified conditions. If this drop occurred through a tree ten meters high, there would be an average force tending to pull water up the tree of 12.6×10^5 dynes per gram, a force approximating 1300 × gravity. Edlefsen concluded that practically the entire drop in free energy occurs near the leaf surface. GRADMANN [1928] reached the same conclusion.

The cause of failure of the plant to obtain enough water from the soil at the permanent wilting percentage may be explained by the position of the permanent wilting percentage on the energy soil-moisture curve in the region where a slight decrease in moisture content results in a great increase in resistance to removal of the water. The supply of water may also fail because of the slowness of movement of water into the mass of soil dried by the roots. Another cause of water deficiency at soil-moisture contents near the permanent wilting percentage may be the failure of roots to elongate rapidly enough into regions where there is still water above the permanent wilting percentage.

The relation of transpiration and soil moisture, however, cannot be determined by purely *a priori* reasoning. The question must be settled by empirical trials with growing plants either in containers or in the field, the latter being the preferable procedure.

The following records are taken from our experiments with trees. Figure 1 is the record of the transpiration of water by a prune tree in a tank sealed to prevent surface evaporation losses for an entire growing season. The weight of the tank at field capacity was 1161 pounds and when

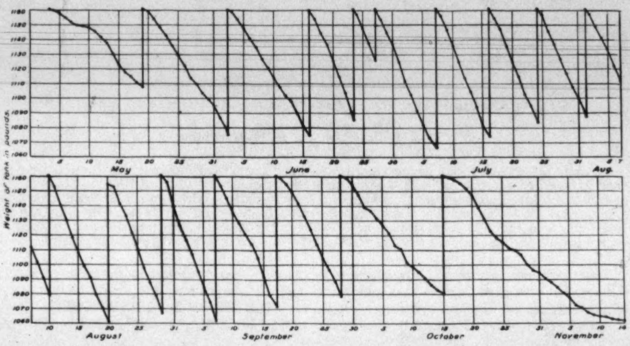

Fig. 1--Transpiration by a prune tree in a sealed tank; the slopes of the graphs indicate the rates of transpiration; decrease in the weight of the system is a decrease in the soil-moisture content

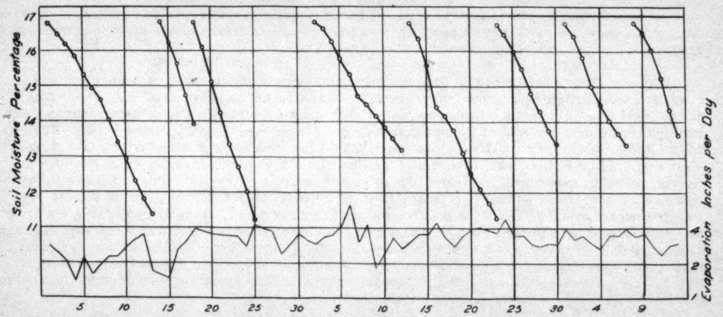

Fig. 2--Transpiration by a pine in a sealed tank; the slopes of the upper graphs indicate rates of transpiration; the broken line at the bottom is the evaporation from a Class A pan

enough water had been extracted by the plant to reduce the soil moisture to the permanent wilting percentage, it weighed 1074 pounds. The slopes of the graph indicate the rates of transpiration. They are no greater immediately after irrigation when the soil moisture was at a high level than just before water was applied which usually was just before the permanent wilting percentage was reached. A further example of the independence of transpiration rates and the amount of moisture in the soil above the permanent wilting percentage is shown in Figure 2. This is the record of a pine tree in a sealed tank. It was an Aleppo pine (Pinus halepensis) which had been placed in the tank a year previous to the time for which the record in Figure 2 is given. The field capacity of the soil in the tank was 16.8 pct and the permanent wilting percentage about 10.5 pct. The whole system weighed about 2500 lb and there was about one ton of soil in the tank.

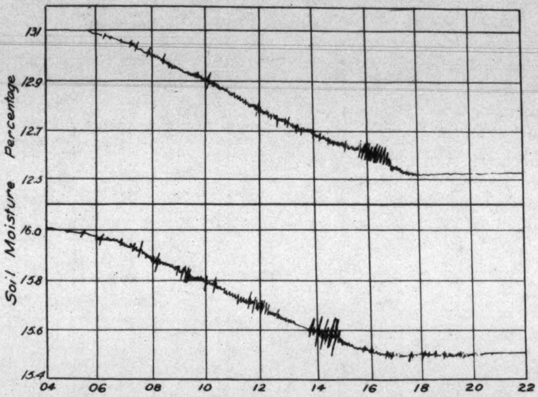

Fig. 3--Transpiration by the pine tree for July 20, upper graph, and for July 25, the lower graph; the irregularity of the lines of the graphs is due to the effect of the wind on the automatic weighing device used to obtain the losses of water from the tank.

The evaporation record for a Class A evaporation pan is given to indicate the evaporation conditions. The changes in rates of transpiration as indicated by the slopes of the graphs are related to those of evaporation and not to soil-moisture changes.

The prune tree and pine tree of Figures 1 and 2 were suspended on a scales so that a continuous automatic record of transpiration was obtained [VEIHMEYER, 1927]. The records for two days for the pine tree are shown in Figure 3. The upper one for July 20 was taken when the moisture content of the soil was between 13.1 and 12.5 pct. This is compared to the record for July 25 when the soil moisture was between 16.0 and 15.5 pct. The slopes of the curves are almost identical.

A record of soil-moisture changes on a watershed on which pine trees, oaks, and manzanita were growing is given in Figure 4. That from an apricot orchard is shown in Figure 5, and the record from a prune orchard is given in Figure 6 for the average soil moisture in the top six feet of soil.

The moisture extraction curves for the first foot of soil in Figures 4 and 5 at the beginning of the season are steeper than for the other depths at this time and also for some of the other times during the record period. This is because of some drainage and to surface evaporation as well as transpiration. These three combined account for the steep slopes of the curves but certainly it is evident that transpiration is independent of the soil-moisture content when it is above the permanent wilting percentage.

Records have been given for both annuals and perennials other than trees [HENDRICKSON and VEIHMEYER, 1945; 1948] which show as do those for trees that the rate of moisture extraction is not influenced by the amount of water present in the soil when the soil moisture is above the permanent wilting percentage.

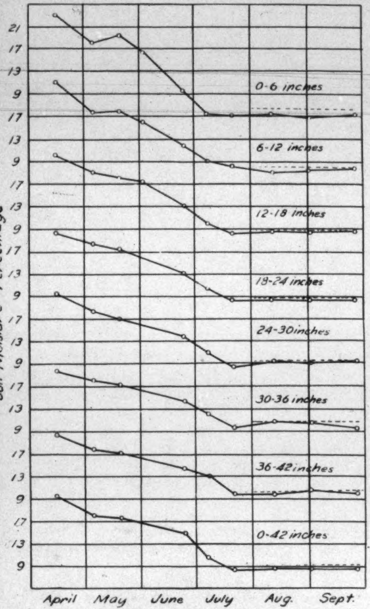

Fig. 4--Soil moisture on a watershed of pine, oak, and manzanita; the permanent wilting percentage is indicated for each depth of soil by the horizontal dotted lines; there were rains just before the samples were taken in April and just after those in the first week in May

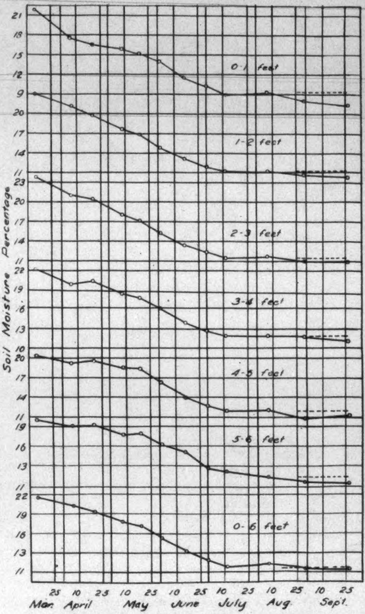

Fig. 5--Soil moisture in an apricot orchard; the permanent wilting percentage is indicated for each depth of soil by the horizontal dotted lines

(See References at end of discussion)

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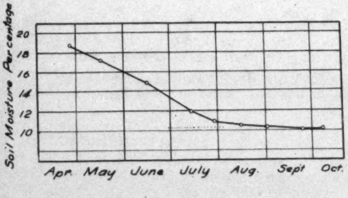

Fig. 6--The average soil moisture in the top six feet of soil in a prune orchard; the permanent wilting percentage is indicated by the horizontal dotted line

DISCUSSION

E. A. Colman (U. S. Forest Service, P. O. Box 245, Berkeley 1, Calif.)--The authors answer to the question is 'No.' I do not think that this unqualified answer can be accepted as the correct on theoretical grounds, on the basis of the data presented by the authors, or on the basis of data from at least one soil-moisture study that was not cited in their statement.

The real question, I think, is what effect does moisture content have upon transpiration rate when the soil is near the wilting point, not what effect does it have well within the range of moisture available to plants. In other words, does transpiration continue at the same rate until the wilting point is reached and then drop abruptly, or does the rate decrease progressively as the soil dries below some moisture content in the lower portion of the 'available' moisture range?

From the shapes of typical moisture content-moisture tension curves, we know that tension increases quite slowly as moisture decreases in the higher portion of the available moisture range. I would not expect transpiration rate to be affected measurably by decreases in moisture content in this portion of the moisture range. As moisture content approaches and goes below the wilting point, tension increases more and more rapidly with decreasing moisture. It is at moistures slightly greater than wilting point, that I would expect tensions to reach values great enough to begin to affect transpiration rate. It is here also that I would expect decreasing permeability to affect markedly and increasingly the rate of supply of water to plant roots, and hence transpiration rates. I cannot specify the particular moisture content in any soil at which decreasing moisture should be reflected in decreasing transpiration rates significantly, but this should be susceptible of determination from moisture-tension relations and moisture-permeability relations.

The figures presented do not show with equal clarity the influence upon evaporative losses of soil moisture throughout the available moisture range. Most of them stress evaporative water losses in soil well above that level. The lines in Figure 1 pass the wilting point weight (1074 pounds) only a few times; also the data in that figure are for a mass of soil of some depth, and the moisture may not have been depleted at equal rates at all depths within it. Decreasing rates are shown as the soil dried in November, when the soil dried for longer than it had at other times. Figure 2 shows no soil moisture close to the wilting point. Figure 3 is also for soil well above the wilting point.

Figures 4, 5, and 6 do generally show evapotranspiration rates decreasing as the wilting point is approached. In Figure 4 the late July points are sometimes below those in August and September, which lends some uncertainty to the preciseness with which moisture contents are estimated in the samplings shown. These last three figures do not seem to bear out the contentions of the authors very well; in fact, they should lead to opposite conclusions.

The theoretical discussion in the third and fourth paragraphs do not come to conclusions that relate to the question I have suggested as the real one. The third paragraph does not end with any support for the conclusion presented in the second sentence. The fourth paragraph suggests, at least, that transpiration rates should decrease as soil dries in the neighborhood of the wilting point. The closing paragraph of the paper does not seem to be supported by the data presented in the figures, nor, for that matter, by the discussion of the figure data which precede this paragraph.

One bit of field data which might have been cited in the authors' presentation is included in a recent publication by ROWE and COLMAN [1951]. Three charts are presented in this publication showing moisture changes during the year under three kinds of wildland vegetation, two in the Sierra Nevada foothills and the other in the mountains of Southern California. The charts show progressive soil-moisture reductions during the dry season by one-foot depth increments in soils three, five, and six feet deep. All the charts show the rate of moisture reductions (caused by evapotranspiration) at each depth decreasing as the soil dries. Rates of water loss decrease most markedly as the soil in each depth layer approaches the wilting point. These data suggest rather strongly that evapotranspiration rate is influenced by soil moisture content, especially in the drier portion of the 'available' moisture range.

C. H. M. van Bavel (North Carolina State College, Raleigh, N. C.)--Perhaps a distinction should be made between transpiration as a physiologic process and as a hydrologic phenomenon. The latter would comprise, in addition to the plant factor, the ecologic and climatologic conditions. Without a doubt, transpiration as a physiologic process is studied preferably with plants growing in containers under controlled conditions. Experiments done in such a manner have been reviewed by KRAMER [1949] and are indicative that transpiration rates decrease before the soil has dried out to the permanent wilting percentage. Work done with solutions with high osmotic pressure suggests that the explanation for reduced transpiration is to be found in the increased value of the diffusion pressure deficit at the root surface, rather than to the decreased rate of moisture movement to the roots or the ability of the latter to reach areas where moisture was still available.

When transpiration is viewed as a hydrologic phenomenon, that is, the manner in which natural soils under field conditions dry, when surface evaporation and drainage are absent or negligible, the question should be settled, as Veihmeyer and Hendrickson point out, by obtaining measurements in the field. This author is of the opinion that the data supplied in Figure 1, 2, 4, and 5 in some cases affirm the position of Veihmeyer and Hendrickson and in others leave it in doubt, or actually contradict it. In Figure 1, the slope of the decumulative curve seems quite well constant up to the wilting percentage, but in Figure 2, the latter condition is never reached, so that there the evidence is not conclusive, one way or another. In Figures 5 and 6, a gradual decrease of the slope of the lines when these are approaching the wilting percentage is, in several cases, evident. Just how conclusive this sort of evidence is, remains to be seen. If the weather conditions had been different during the period of observation, the shape of the lines would have been different accordingly. If experiments could be carried out where adjacent areas with high and low soil moisture content could be compared during the same time period, the data would be more conclusive. Also, moisture characteristics of the soils involved would elucidate the data considerably.

From a practical point of view, there is much to be said, in the opinion of this writer, to assume transpiration to be independent of moisture content, provided the greater part of the moisture storage capacity occurs at low moisture stresses, say below two atmospheres. When the latter stress is greater, the matter appears to be undecided by the available evidence.

R. B. Marston (U. S. Forest Service, Wasatch Research Center, Farmington, Utah)--A field study of ours on unirrigated aspen-herbaceous sites in northern Utah suggests that there is a decrease in evapotranspiration rates in the fall when moisture is available only at the deeper soil levels.

H. A. Wadsworth (University of Hawaii, Honolulu, Hawaii)--Work with sugar cane grown in tanks similar to those used by Veihmeyer and Hendrickson indicated a uniform rate of loss of water by transpiration throughout the entire range of the so-called available soil moisture. Sealed tanks were weighed daily. When plotted against time daily weighings traced straight lines betweeen the gross weight associated with maximum field capacity to that associated with the permanent wilting point as determined by sunflower tests on the soil involved. As in the work reported by Veihmeyer and Hendrickson the slopes of the lines varied with the climatic conditions and the sizes of the cane plants. But over the periods covered by a simple irrigation the lines were essentially straight. This characteristic was evident throughout the normal crop length of twenty months.

The only precise work on rates of transpiration with plants grown in Hawaiian soils indicates that transpiration does not decrease as soil moisture decreases within the limits specified in the paper by Veihmeyer and Hendrickson.

Stephen J. Mech (Irrigation Experiment Sta., Prosser, Wash.)--The evidence presented supports the negative answer the authors give to the question. On the other hand plant physiology literature is so full of contrary statements based on equally good work done by others that exceedingly strong proof will be required to establish the opposite viewpoint. Had the paper shown transpiration rates on a daily basis it would have shown more effectively any differences that might have occurred during the period of measurement.

It is difficult to reconcile the conclusions in this paper with numerous observations of color changes of vegetation usually associated with soil moisture. Dark green in potatoes and in alfalfa and a grayish-green in wheat are generally expressions of a reduced soil moisture condition but a condition still considerably above wilting point. After irrigation this vegetation will turn a light, lush green. Such color changes are generally accompanied by greater turgor and suggest a physiological change in the plant.

We have also found positive relationship between moisture in the soil and the moisture content of vegetation. The dry matter content of corn and alfalfa plants was greatest where the soil moisture was lowest. The plants from the areas of higher soil moisture showed a lower dry matter content.

We have considerable data which show that 'consumptive use' very definitely decreases as the soil moisture content before irrigation is decreased. The consumptive use is higher on a crop irrigated when 40 pct of the available moisture in the four-foot root zone has been depleted than it is when irrigation is delayed until 65 pct of this moisture is lost. A sugar beet field whose available soil moisture before irrigation was not permitted to drop below 60 pct had a consumptive use of 46.2 inches per year. Where this moisture was permitted to drop to 35 pct before irrigation it amounted to 36.7 inches. Where it was not irrigated until it was 85 pct depleted, the use was 32.0 inches during the season.

The above results were based on soil moisture samples taken 60-72 hr after irrigation water was turned off and one day before the next irrigation began. The time not covered by this interval was estimated by interpolation. It was assumed that by waiting the 60-72 hr the soil profile would reach field capacity. Of course, by definition, field capacity implies a continuing downward movement of moisture though at a materially decreased rate. In an irrigation designed to fill the root zone, this continuing downward movement becomes deep percolation loss.

The consumptive use obtained in the above manner consists therefore of three components, (1) such surface evaporation as may occur after the 60-72-hr waiting period, (2) the transpiration between sampling dates, and (3) such soil moisture movement below the sampling depth as may take place between the two sampling dates.

The first two factors are included in the usual definition of consumptive use or evapotranspiration, but the third (loss below sampling depth) while inherent in all but those cases having an impervious barrier within the sampling depth, is omitted from the definition. While this percolation loss is generally included by implication in most consumptive use results, it is usually ignored as a factor because the definition of field capacity implies that downward movement after a two- or three-day waiting period is negligible.

The absolute magnitude of such loss is small. However, the procedure used in arriving at the total season's use places increased importance on this loss. For example, a loss of 0.5 inch below the sampling depth would increase the consumptive use rate 0.05 inch per day under an irrigation frequency of ten days. A similar field on a 25-day irrigation schedule would have an increase of only 0.02 inch per day.

Because of the influence of this downward movement on the daily use, it is possible to obtain one consumptive use value on a soil with no restrictions in the profile and a somewhat lower consumptive use on an adjacent field that has a restriction within the root zone. The surface evaporation and the transpiration should be identical on both fields. The restriction prevents any further downward movement, thereby eliminating the loss and producing a lower consumptive use. From the practical standpoint the irrigator and engineer are interested in the consumptive use of agiven field. The correct answer to the question raised in the title of the paper would be a big step in the progress toward the solution of the consumptive use question.

A. R. Croft (U. S. Forest Service, 2886 Van Buren Ave., Ogden, Utah)--In appraising the results of studies which support the contention of the authors, the thermodynamic approach to explanation of the movement of water in plants as presented by EDLEFSEN [1941] should not be overlooked. Edlefsen points out that in discussions of the use of soil moisture by plants the soil scientist and plant physiologist do not use the same language. The soil scientist has developed a language composed of terms which describe the state of moisture in the soil under given conditions. Considerable duplication of terms exists.

Likewise, the plant physiologist uses a variety of terms for describing the state of moisture in the plant. Here also there is considerable duplication and no little ambiguity of terms. "This difference in language has no doubt developed because the two fields of study have progressed almost independently of each other." Edlefsen goes on to point out that in the study of the use of soil moisture by plants "one may currently consider the soil, plant, and air as a combined system (to which) the language of thermodynamics has been well developed and tested and is admirably adopted for such a system."

Although Edlefsen's formulas cannot be followed except by a mathematician, his reasoning and application of the values developed leave little doubt that tremendous energy exists within a plant tending to pull water upward and that practically the entire drop in energy occurs near the leaf surface. This reasoning lends valuable theoretical affirmative support to the question, because it gives what appears to be a sound basis for it.

Understanding the complex relations of water in the soil-plant-air system would be greatly improved by the development of a common terminology suitable for the needs of workers in the closely related fields of soil-moisture physics and plant physiology.

C. M. Woodruff (University of Missouri, Columbia, Mo.)--The conclusion reached by Veihmeyer and Hendrickson, appears to be substantiated, not only by the arguments and results which they present, but also by other considerations. Measurements of moisture losses from full grown corn, through a seven-week period without rain at the Missouri Experiment Station, revealed that the moisture losses from the soil amounted to one inch per week throughout the period. The rate of loss at the end of the period when the moisture content of the soil profile had been reduced to the wilting point to a depth of 3.5 feet was equal to the rate of loss at the beginning of the period when the soil was at field capacity.

Results of measurement of water consumption by bluegrass on a two-acre watershed equipped with runoff measuring devices, showed an average daily consumption of 0.14 inch through the three growing seasons of 1950, 1951, and 1952. The only deviations from this rate of loss occurred when after prolonged drought the bluegrass turned brown.

The energy with which water is retained by the soil, even at the wilting point, is so small in comparison with the energy available for withdrawing water from the soil as suggested by the computations of Edlefsen that the rate of transpiration of moisture by unwilted plants appears to bear no relation to the tightness with which water is held by the soil.

Although many investigators call attention to the moisture deficit of the air as the driving force responsible for the transpiration of water by plants, the relatively constant rate of transpiration of water from a large area shaded by green foliage through three different seasons, representing both mois and dry periods, suggests that the relative humidity of the air exerts at most only a secondary effect on the rate of transpiration of water by vegetation.

Transpiration like evaporation is a cooling process. In order to vaporize 0.14 inch of water per day, 206 calories of energy would be required for each square centimeter of land surface. This amount of energy extracted from the overlying air would result in a 5°C drop in temperature to a height of nearly one mile, which is not a likely possibility. The transfer of energy from the air to the vegetation must be limited to a small fraction of the total that is required for the transpiration of 0.14 inch of water per day.

A plant leaf in a saturated atmosphere at 30°C receiving sufficient solar radiation to raise the temperature of the leaf surface 1°C above the surrounding air would increase the vapor pressure of the water in the leaf by 1.89 mm of mercury. This increase would be sufficient to create a free-energy change of -0.81×10^8 ergs per gram of water. Subtracting the free energy change of the moisture in the soil at the wilting point -0.16×10^8 leaves a net driving force of -0.65×10^8 dynes/cm^2 for the movement of water through the plant. A temperature rise of 1°C for the leaf surface is small compared to the rise that would be experienced by any inert heat-absorbing surface exposed to the Sun's rays. Hence one must conclude that under any condition of the relative humidity of the atmosphere, the energy available for the transpiration of water from a leaf surface exposed to the Sun is far in excess of the energy required to extract water from the soil at the wilting point and in all excepting the arid regions where the winds sweep over nonevaporating or nontranspiring surfaces, the rate of transpiration must be conditioned by the incident solar radiation rather than by the relative humidity of the air. One would conclude along with Veihmeyer and Hendrickson that any moisture tension of the soil that was sufficient to keep the plant in an unwilted condition would be sufficient to maintain a constant rate of transpiration.

N. L. Stoltenberg (Purdue University, West Lafayette, Ind.)--The data presented by the authors are strong evidence supporting their conclusion . This conclusion must be tempered, however, by a recognition of the considerable background of data, using a wide variety of plants and methods, which has led other investigators to a different conclusion. The reason for lack of agreement may well be due to the large number of varying environmental conditions which affect transpiration rates. Reference may be made to the work of HAYNES [1948], BLAIR and Others [1950], and WADLEIGH and GAUCH [1948] in which a number of these environmental factors were controlled.

One important environmental condition is the nutrient status of the soil. A decreasing nutrient supply would explain some cases of decreased transpiration at lower moisture contents. On the other hand, if a nutrient deficiency is limiting plant growth, differences in transpiration rate due to the soil-moisture level may not be evident.

The plants used in studies of transpiration losses are also changing, extending their leaf surface and roots as soil moisture decreases. In field studies the extension of roots may compensate for possible effects due to changes in the soil-moisture level. In future studies which attempt to rationalize the anomalies apparent in the present status of our knowledge of plant-water relations, the conditions affecting plant growth should be clearly defined.

The loss of moisture by evaporation from the soil surface may be very small compared to transpiration losses but the importance of these losses should not be underemphasized in considering improved land use. We have measured a decrease in evaporation loss amounting to 0.4 inch per month while increasing the yield of soybeans from 34 to 43 bu per acre. Likewise the decrease in evaporation loss from land in wheat producing 41 bu per acre as compared with that producing 27 bu per acre amounted to 1.3 inches per month. The measurements were made during July and August when soil moisture frequently limits crop yields.

The decreases in evaporation losses are presumably due to increased shading and decreased air movements. It should be noted that the water saved by reduced evaporation due to greater crop growth in turn becomes available for greater crop growth.

L. D. Doneen (University of California, Davis, California)--This question is difficult to answer with some annual crops. The following discussion is limited to transpiration and soil-moisture studies of field-grown crops. Annual plants present many problems, such as the continually enlarging root system and the difficulty in determining the exact volume of soil actually occupied by their roots. Some plants develop shallow root systems, others extremely deep ones, ten feet or more. The plants with vigorous roots permeate the soil mass with many fine roots and can utilize the moisture of all of the soil to the permanent wilting percentage, whereas the less vigorous or sparse root system occupying only portions of the soil mass cannot utilize all the available moisture before wilting or cessation of growth occurs. Many plants root deeply with a few roots but fail to permeate the soil mass thoroughly, and water must move through the soil to the root, an extremely slow process. With this type of plant, the average moisture content of the soil does not give a true picture of the soil in immediate contact with the roots. Certain plants have been found to have poor or sparse root systems for a part of their life cycle, but as they reach fruiting or maturity, this skeleton root system is gradually filled in with many fine fibrous roots. If soil moisture-transpiration studies are made with plants having this skeleton root system, the results may show an apparent decreasing transpiration with decreasing soil moisture. At a later date, when the roots have permeated the soil mass, there will be no difference in transpiration rates with decreasing soil moisture until the permanent wilting percentage is reached.

Another complicating factor in this study is the 'zone of root transition.' This is the area between the soil which is well permeated with roots and that at the tip of the farthest growing root. This zone contains a varying concentration of roots, usually with a gradual decrease in concentration as the distance increases from the permeated area. This transition zone may be limited not only in depth but also horizontally. For isolated plants, it forms a periphery around the area permeated with roots. If plants grow together closely, this transition zone is usually only in depth. However, with some row crops a transition zone may exist between the rows. The percentage of the total rooting area the transition zone occupies varies with the plant and the soil conditions. For some plants it will be less than 25 pct; with others, it may range to 100 pct for those plants developing only a skeleton root system. The planting date is important in this type of study. A crop planted in the late winter or early spring may develop an extensive and dense root system with a small percentage of the rooting areas in the transition zone by the time warm weather with high transpiration rates occurs. This same crop planted two or three months later under warm climatic conditions may develop only a small skeleton root system before wilting. Studies show that crops planted in the cooler coastal areas where transpiration rates are low will have a smaller percentage of the root system in the transitional zone than those planted in the hot interior valleys where transpiration rates are high. Even varieties within a species show marked differences in depth of rooting and the transitional root zone.

Veihmeyer and Hendrickson's results are with permanently rooted crops which are ideally suited to this type of study. Three of their examples, furthermore, are in large containers which eliminate the transition zone. Even with perennials or permanently rooted crops, there is some transition zone in deep open soils, but this is usually small in comparison with the large volume of soil thoroughly permeated with roots. Besides this transition zone is fairly constant and can, therefore, be delineated.

To appraise transpiration versus soil moisture, alfalfa was selected. This is a deep rooted crop utilizing the soil moisture to a depth of ten to 12 feet before a reduction in growth occurs. The tap root grows considerably deeper than this and will provide the plant with moisture to sustain life, but growth practically stops when the top ten to 12 feet of soil is dried to the permanent wilting percentage. Figure 7 shows the use of water for alfalfa for 12 ft of soil plotted as an accumulative curve. The record was started after the spring rain and no water was applied. Three crops were harvested on April 26, June 7, and July 16. The soil moisture dropped from about 20 to 11 pct. The first two harvestings showed no difference in yield when compared to plots frequently irrigated. The third harvesting on July 16 showed a slightly smaller yield. A slowing in growth with a change in color of the foliage could be noted by July 9. At this time the upper eight feet of soil was reduced to the permanent wilting percentage. The slight reduction in the curve after June 4 may be due to two factors: (1) the alfalfa was cut for hay on June 7 with nearly a total loss of leaf area (which requires two to three weeks to recover); and (2) a two-week period of cool weather occurred at this time as indicated by the average of maximum temperatures between the soil sampling periods. But it should be noted that the rate of extraction increased after June 25 when it equalled the maximum rate reached just before the previous harvest.

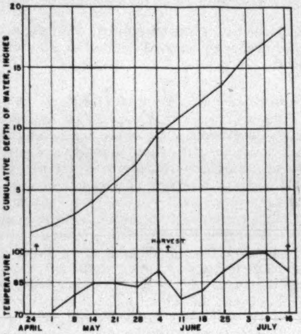

Fig. 7--The accumulative use of water in inches depth for alfalfa and the average daily maximum temperature (°F) for the period preceding the sampling date; there was no irrigation during the period for which this record is given; the average soil moisture for the top 12 feet of soil was 20 pct on April 24 and was reduced to 11 pct on July 16

After investigating the use of soil moisture under field conditions of some 20 field and vegetable crops, the conclusion drawn is the same as that of Veihmeyer and Hendrickson, "that the rate of moisture extraction is not influenced by the amount of water present in the soil when the soil is above the permanent wilting percentage," provided the plants do not have a poor or skeleton root system and the transition zone of root development is not included.

J. R. Mather (laboratory of Climatology, Elmer, N. J.)--Although the authors argue that *a priori* reasoning should not be used to settle the question, it is clear that empirical tests will also not provide answers which will convince everyone. The interpretation of the results of field experiments is in many cases open to question and with the number of field tests increasing there will probably always be a number which show clearly, although mistakenly, wide discrepancies in the results.

Most of the data presented by the authors in this paper have appeared before and may be questioned on several counts. First, as the authors themselves say, container experiments are unnatural and the results should not be taken as conclusive. The field tests shown in Figure 4, 5 and 6 are interesting but they do not provide a conclusive answer to the question. Consider Figure 6 more specifically. Although the slope of the soil-moisture content line would indicate that moisture was being removed from the soil at a constant rate until the permanent wilting percentage is reached, in actuality it shows a progressive reduction in the rate of removal of water. The reason for this is that as the season advances from April to July the temperature increases with a corresponding increase in the rate of potential evapotranspiration. Although an increase in the rate of water loss from the soil is to be expected because of the warmer conditions in June and July the rate of water loss from the soil remains unchanged. There is a greater opportunity for evaporation in those months, yet the measured soil moisture change shows no increase. Thus, in effect it reveals a relative decrease in the rate of water use by plants. Figure 8 below shows this point more clearly.

Records from our evapotranspirometer tanks at Seabrook, N. J., also give us considerable information on the relation between water use and soil moisture. Although the soil in all tanks is maintained near the field capacity, those tanks receiving the most water give the highest value of water use. The results of this work for 1951 were summed up briefly in the report for 1951-1952 of the Committee on Evaporation and Transpiration of the American Geophysical Union. Results for 1952 are summed up in the Table 1.

Table 1--Results of Seabrook evapotranspirometer tests in 1952

Tank	Jan.-Mar.		Apr.-June		July-Sep.		Oct.-Dec.	
	WA[a]	ME[b]	WA	ME	WA	ME	WA	ME
	mm	mm	mm	mm	mm	mm	mm	mm
Tanks A, B, C, D	322	58	478	294	606	387	330	132
Tanks E, F	348	65	638	344	817	408	462	124
Tank G	445	81	705	380	902	473	454	130

[a] Amount of water added

[b] Measured evaporation

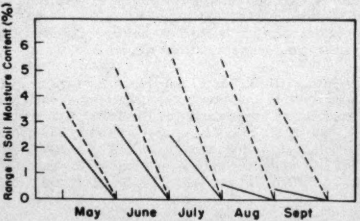

Fig. 8--Average monthly rate of soil-moisture depletion in top six feet of soil in a prune orchard; solid line indicates measured rate of depletion (obtained from Fig. 6) while dashed line indicates rate of depletion which would have occurred had moisture been lost at potential rate. Increasing difference in slopes of lines may indicate progressive reduction in the rate of soil moisture depletion because of the drying of the soil

Tanks A, B, C, and D have a permanent water table at 25-35 cm below the surface of the ground while tanks E, F, and G have no water table but are irrigated from above enough to insure a small amount of daily percolation. All tanks have a bluegrass and clover vegetation cover. The data in the table indicate a direct relationship between evapotranspiration and soil-moisture content in even very moist soil during the period of most active growth from April through September. No definite relation can be found during the late fall and winter months when the vegetation is essentially dormant.

In a recent study of this same problem ALPATIEV [1952] shows from his own work as well as from that of other Soviet scientists that the low limit of optimum soil moisture for various crops on fine textured soils is not less than 60-70 pct of field capacity. The low limit for sandy loam is about 50 pct of field capacity while for sandy soils it is somewhat below 50 pct.

Sterling A. Taylor (Utah State Agricultural College, Logan, Utah)--In a recent article Ashcroft and the writer [ASHCROFT and TAYLOR, 1953] report data which show that the rate of removal of water from the soil is highly correlated with weather factors. The speed of evaporation and transpiration depends directly on the vapor-pressure gradient and on the coefficient of diffusion. Weather factors control the vapor-pressure gradient to a large degree, but have only a secondary effect on the coefficient of diffusion which is largely a function of the physiological condition of the transpiring plant.

If two plants growing side by side are alike in every respect except that one is in a soil containing water at a higher tension than the other, the vapor-pressure gradient between the plant leaves and the atmosphere will be the same. It can be reasoned that the vapor-pressure inside the leaf which is not wilted is at 100 pct relative humidity and depends only on the leaf temperature which in this case would be the same. If neither leaf is wilted the stomatal openings would be the same, hence the diffusion coefficient would be alike in both cases. If both the vapor-pressure gradient and the diffusion coefficient are the same, like amounts of water will be evaporated from both plants. This will continue until one of the plants wilts; at this time vapor-pressure gradient will not greatly change but the coefficient of diffusion will be reduced in proportion to the reduction in pore space that is open to diffusion. As soon as the wilted plant recovers, however, the transpiration will again be the same. If a plant remains wilted only a small portion of the time, just a slight difference in removal would be present and a very highly refined experiment would be required to detect this single occurrence.

In the case of Veihmeyer and Hendrickson's experiments, it is quite probable that the fluctuations resulting from environmental changes were greater than any retardation that might have been attributable to temporary wilting and no change in slope of the curves could be detected.

In 1949 an experiment was established at the Utah Experiment Station in cooperation with the eleven Western States, Hawaii, Alaska, the Bureau of Plant Industry, Soils and Agricultural Engineering, and the Soil Conservation Service (Research). Crops were irrigated by both sprinkler and furrow types of irrigation. Plots were irrigated independently whenever the soil moisture in plant root zone as indicated by plaster resistance blocks or tensiometers had been reduced to the following levels: (1) 75-90 pct of the available water had been removed; this corresponds to a moisture tension of about eight to ten atmospheres; (2) 50-70 pct of the available water had been removed or about four to six atmospheres had been reached; (3) 30-35 pct of the available water had been removed or a tension of 0.6 to 0.8 atmosphere had been reached; and (4) 10-15 pct of the available water had been removed or a tension of 0.2 to 0.3 atmosphere had been reached.

The amount of water applied to the soil was measured. The amount removed by plants was calculated by the method of Ashcroft and Taylor. Whenever there was evidence of water loss by deep percolation, the data were set aside. The remaining data collected from three years of field work indicate that from ten to twenty pct more water was removed from the soil by alfalfa, sugar beets, and potatoes that were grown on soils that were moist a larger portion of the time, than those grown on soils that were allowed to become dryer before irrigation applications were made.

Leon Lassen, Howard W. Lull, and Bernard Frank (U. S. Forest Service, Washington, D. C.)--Veihmeyer and Hendrickson have repeatedly answered this question in the negative, on each occasion presenting soil-moisture drying records, portions of which exhibited linearity. Their view has had a mixed reception. Other recent works, in addition to the two papers cited by the authors, uphold the affirmative side of the question. These include widely used textbooks on soils by LYON, BUCKMAN, and BRADY [1952] and RUSSELL [1950], and detailed considerations of the question, including reviews of the literature, pro and con, by RICHARDS and WADLEIGH [1952] and KRAMER [1949].

Reviewing Veihmeyer and Hendrickson's individual points, first, Edlefsen's [1941] work hardly appears pertinent to the question under discussion for, as the authors themselves indicate, practically the entire drop in free energy occurs near the leaf surface. RICHARDS and WADLEIGH [1952] have dealt with this point, concluding that 'the range of soil moisture stress observed in soils is of the same order of magnitude as the diffusion pressure deficit range found in plants.'

The authors then note that one reason why plants do not obtain enough water at the permanent wilting percentage is that, with a slight decrease in moisture content, a great increase occurs in resistance to removal of water. We agree but wonder why, with this reasoning, resistance should so suddenly become effective at the permanent wilting percentage.

It seems to us that the authors have underestimated the value of a priori reasoning in seeking substantiation of their thesis. Empirical tests by themselves do not explain the 'whys' of given phenomena, nor do the results necessarily yield basic principles. The value of empirical tests depends largely on how adequately they cover the wide range of variations in natural phenomena, and the extent to which the results can be verified by tests made by other investigators. Thus the curves presented in this discussion (Fig. 9), reflecting the results of a much larger number of tests, do not jibe with those presented by the authors. What conclusions should we then draw from the authors' generalizations derived from their empirical approach?

Perhaps still more important to investigations in this field, where full control of the environmental factors, both above and below the surface, is obviously impossible, is the necessity for describing quantitatively, in as great detail as possible, those environmental factors which may not only affect the findings, but may also help explain apparent discrepancies between findings from different experiments.

For example, the results of the tank experiment with the prune tree would have appeared more meaningful if such supplemental factors as the following had been supplied: (1) The increase in dry weight of the tree during the months of measurement. It is quite possible that the moisture content determinations may have been affected by this one factor alone. (2) The impact of air temperatures on the tanks, and the effects of such probable differences in temperature on the soil in the tanks (by comparison with temperatures of the soil in situ) on the characteristics of the tension-moisture relations. For instance, higher temperatures prevailing in the tank experiments would tend to reduce the energy requirements for moisture extraction, with a corresponding effect on evapotranspiration rates. (3) The progress of root elongation of the plant, particularly the changes in volume of soil space occupied by the root mass during the period of measurement. This factor, too, may have effected the shapes and slopes of the curves shown in Figure 1.

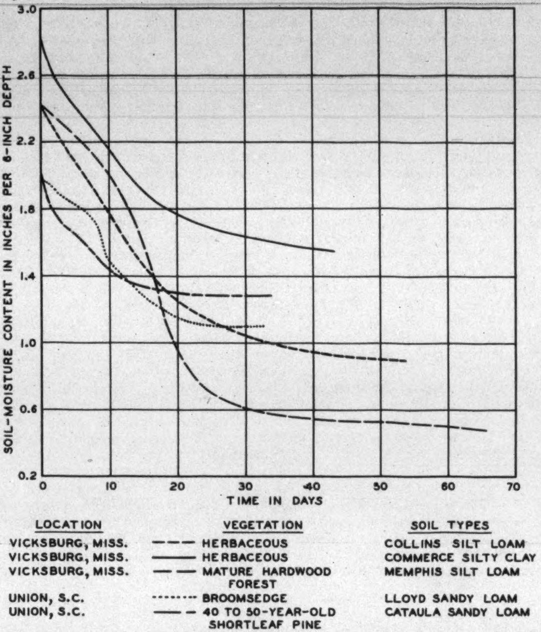

Fig. 9--Average soil-moisture drying curves for the six- to twelve-inch depth

We note that in several cases the moisture contents shown in Figures 1 and 2 do not reach the wilting percentage. Nor do we understand why other curves do not flatten out when the moisture content does reach that level.

The many serious limitations inherent in the conduct of tank or pot experiments--including among other handicaps the artificial characteristics of soil-root relations, and lack of competition with other plants--lead us to agree with the authors' preference for field procedures.

When we examine the curves derived by field procedures (Fig. 4, 5, 6) definite evidences of curvilinearity appear. A more frequent recording of changes in moisture content that those shown in Figures 4 and 6 would undoubtedly have permitted a more adequate determination of this tendency. (It is interesting to note that we used soil-moisture drying curves presented by HENDRICKSON and VEIHMEYER [1945] to illustrate that evapotranspiration decreases as the soil moisture decreases [LASSEN, LULL, and FRANK, 1952]).

As mentioned above, other investigations indicate that the general shape of the curves presented by the authors is by no means characteristic of all soil-cover complexes. Soil moisture drying curves presented by ROWE and COLMAN [1951] show a definite decrease in moisture loss with decrease in moisture content. The drying curves for five sites near Vicksburg, Mississippi, and Union, South Carolina, illustrated in Figure 9 also exhibit a strong curvilinearity.

In conclusion, neither our a priori reasoning nor the experimental results which have been available to us up to the present time support the authors' views. On the contrary, the data indicate that our own conclusions are more nearly correct. Currently, the Forest Service is undertaking a comprehensive field study of soil moisture involving daily measurements at 110 sites representing a wide range of soils and climatic conditions. This study is scheduled for completion within the next two years at which time the results will become generally available. These findings should do much to clarify the question of how much transpiration decreases with decreases in soil moisture. Meanwhile, a statement by SPALDING [1903] almost a half century ago is worth repeating: 'With so complicated a problem general statements may well be made with extreme caution, but the evidence in the present case is sufficient to show that in studies of transpiration it is altogether unsafe to attempt to estimate any other factors whatever without taking due account of water in the soil.'

Paul J. Kramer (Duke University, Durham, N. C.)--The data presented by Veihmeyer and Hendrickson certainly seem to support their claim that in these experiments the rate of water absorption was not reduced by decreasing soil moisture until the soil was dried down to approximately the permanent wilting percentage. I do not believe, however, that this fact justifies their generalization that the rates of absorption and transpiration always remain unchanged over the entire range from field capacity to permanent-wilting percentage. Neither do I believe that these experiments prove that water usually is equally available over the range from field capacity to permanent wilting. A number of investigators have reported quite different results. Space prevents citation of this work, but most of it has been reviewed very thoroughly by RICHARDS and WADLEIGH [1952], and also by VEIHMEYER and HENDRICKSON [1950], who pointed out possible flaws in some of the experiments. KOZLOWSKI [1949] found that the rates of soil moisture depletion and apparent photosynthesis of potted overcup oak and loblolly pine began to decrease with decreasing soil moisture long before the permanent wilting percentage was approached. WENGER [1952] recently grew sweetgum, loblolly pine, and shortleaf pine seedlings in pots with three water regimes. Seedlings of all three species made significantly more height growth and more increase in fresh weight when grown in soil maintained at the moisture equivalent than when grown in soil from which 80 pct of the available water was removed before rewatering. HENDRICKSON and VEIHMEYER [1951, pp. 5 and 13] themselves reported that apricot trees showed greater increase in cross-section area of stems when the top six feet of soil was kept above the permanent wilting percentage than when the top three feet were allowed to dry to permanent wilting before irrigating.

There are several possible reasons why competent investigators have arrived at such contradictory conclusions. One is the difference in shape of the moisture tension-moisture content curves for different soils, as shown, for example, in Figure 18 of Richards and Wadleigh. Olympic clay holds nearly 50 pct of its water with a tension of more than one atmosphere and 25 pct with a tension of over three atmospheres, but Yolo clay loam holds only 25 pct of its water with a tension of more than one atmosphere and less than 15 pct with a tension of more than three atmospheres.

Much of Veihmeyer and Hendrickson's work has been done with plants in Yolo clay loam or similar soils in which the margin between the point where soil moisture begins to be less available and the permanent wilting percentage is so narrow that it cannot be detected in field experiments. For practical purposes water can be regarded as almost equally available over the range from field capacity to permanent wilting. This would not be equally true in soils such as the Olympic clay where nearly half the water is held with a tension of more than one atmosphere and therefore theoretically is less available. Even in this soil, sampling of soil moisture in the field at too long intervals may result in failure to observe any change in rate of water extraction even though it does decrease in the lower part of the range of available water. Another cause for difference in opinion is that much of Veihmeyer and Hendrickson's work has been done with fruit trees which are less sensitive to variations in soil moisture than many herbaceous plants. Futhermore they have generally judged the effects of their irrigation treatments in terms of fruit production which seems to be less affected by water deficit than vegetative growth. They themselves found, for example, that although the best vegetative growth of apricots was obtained with the most frequent irrigations, somewhat less frequent irrigation did not significantly reduce the yield of fruit. In terms of cost of production of some crops (but not all) it may be justifiable to recommend that the soil be allowed to dry down nearly to permanent wilting before irrigating, but this does not justify the conclusion that water is equally available to plants over the range from field capacity to permanent wilting percentage.

Availability of soil moisture depends primarily on the existence of a sufficiently steep DPD gradient from soil to roots to cause the intake of adequate water. The DPD in the roots of cultivated plants usually is less than ten atmospheres and seldom exceeds 25 atmospheres. Theoretically water cannot be equally available over the range from field capacity to permanent wilting because this covers a DPD range from zero to 15 atmospheres in the soil and it has been adequately demonstrated that water uptake and plant growth is often reduced by soil moisture tensions or DPD's of from one to four atmospheres. Much of the data supporting this view has been summarized by KRAMER [1949, pp. 235-241] and by RICHARDS and WADLEIGH [1952], hence only one recent paper will be mentioned here. ARMY and KOZLOWSKI [1951] reported that only about 40 pct of the available water is available to detopped root systems of bean, corn, tobacco, and tomato. The also reported that the transpiration rates of tomatoes were reduced by immersion of the root systems in sucrose solutions having osmotic pressures of only one or two atmospheres. Their findings agree with earlier work of Kramer and McDermott [see KRAMER, 1949].

In field practice CLEMENTS [1948] emphasized the importance of heavy irrigation during the early stages of growth and reported that on certain soils growth of cane is checked by soil moisture tensions of less than an atmosphere. There is increasing evidence that maintenance of soil moisture near field capacity is desirable for maximum vegetative growth of at least some crops.

Veihmeyer and Hendrickson seem to regard small changes in the steepness of the DPD gradient from soil to root as unimportant because they are such a small fraction of the total DPD gradient from soil through the plant to the air. The total gradient may exceed 1000 atmospheres, but most of this difference occurs between the evaporating cells of the leaf and the air and the average gradient from soil to root is probably less than ten atmospheres. A slight increase in DPD of the soil moisture may therefore markedly hinder water intake, as has been demonstrated by the experiments on the effects of osmotic pressure or tension of the substrate on water uptake previously mentioned. On hot sunny days even a small reduction in water uptake can produce a sufficiently large internal water deficit to cause temporary wilting, premature stomatal closure, and reduction in transpiration, photosynthesis, and growth. Plants sometimes show temporary wilting in soil near field capacity and this daily wilting certainly becomes more severe and more injurious as decreasing soil moisture begins to cause an increase in the soil-moisture tension.

My views can be summarized as follows. On a theoretical basis any appreciable increase in soil moisture tension should result in some decrease in water absorption and this has been demonstrated to occur under experimental conditions. Because of the hyperbolic shape of the soil-moisture-tension curve this may or may not be important under field conditions. If most of the available water is held with a tension of less than one atmosphere, then for practical purposes water is equally available almost down to the permanent wilting percentage, but if much of the soil moisture is held with a tension of more than one atmosphere then transpiration and plant growth are likely to be reduced at soil moisture contents considerably above the permanent wilting percentage.

F. J. Veihmeyer and A. H. Hendrickson (University of California, Davis, Calif., Authors' closure)--Our original paper was not intended to be an exhaustive treatment of the subject. Its purpose was to provoke discussion. Obviously it has been successful in this respect. The number of those who took the time to enter the discussion is most gratifying and we thank them for their contribution to this important subject. Space does not permit comments on each point raised by the contributors. We have tried to confine our closing remarks largely to transpiration and not the other effects soil moisture may have upon the plant. We purposely made our paper as brief as possible and only included enough data which we thought would clearly indicate the relation of soil moisture to transpiration. It has been necessary to add additional material on some of the points at issue in view of some of the questions raised by some of those who took part in the discussion.

Colman's discussion indicates that he believes transpiration will be affected only when the soil moisture is slightly greater than the wilting point. Others have made similar statements. The question then is: How close to the permanent wilting percentage can the soil moisture be reduced before transpiration is effected? We have stated elsewhere that the permanent wilting percentage is not an unique value, but is a small range of soil moisture within which wilting takes place. Of course, plant responses are not instantaneous and plants must remain at the permanent wilting percentage for some time before noticeable effects are produced. Furthermore, permanent wilting is not the first sign of wilting, but is that at which the plants will not revive in a moist chamber without the addition of water. It may be reasoned, therefore, that there may be some lessening of transpiration just before the permanent wilting percentage is reached. We point out again that the tightness with which the water is held by the soil does not increase enough to prevent the escape of water from the leaf until the soil moisture content is reduced below the permanent wilting percentage.

The data in Figure 1 show that there was no measurable decrease in rate of transpiration in eight cases when the soil moisture was reduced to the permanent wilting percentage. On two other occasions, the moisture was reduced to within about 0.5 pct of the permanent wilting percentage, namely, to 11.6 pct (the permanent wilting percentage is 11.1), but another time it was reduced to 11.8 pct.

The decreasing rates in November to which Colman calls attention, of course, are due to the defoliation of the tree at this time and the marked decrease in evaporating conditions in October and November.

The roots of the prune tree for the transpiration, as reported in Figure 1, thoroughly permeated the soil in the tanks [see VEIHMEYER, 1927, Fig. 25, p. 199, for a photograph of the roots of this tree]. Sampling the soil in the tank, furthermore, showed as nearly uniform distribution as could be determined within the accuracy of sampling.

The soil moisture in the pine tree tank (Fig. 2) was reduced close to the permanent wilting percentage three times when it was within one per cent of this value.

In any soil moisture determination in the field, the very nature of the material precludes the possibility of measuring the moisture more precisely than within about one per cent of soil moisture for fine textured soils. It is not surprising, therefore, that there are some irregularities in the curves of Figure 4 to which Colman calls attention.

Figures 4, 5, and 6 do show that there is a very wide range of soil moisture throughout which transpiration is not affected. Colman's adverse opinion stems again from his concern about what happens when the moisture is reduced almost to the permanent wilting percentage, perhaps within one per cent of it. Our data certainly do not lead to opposite conclusions as he states.

An examination of the data in the reference cited by Colman reveals that in many cases the rates of transpiration do not decrease as the permanent wilting percentage is reached. Figure 19 of ROWE and COLMAN [1951] is a good illustration of this. From about the middle of April to July 1 the soil moisture extraction is linear with respect to time. In other words, a straight line can be drawn through the points within the tolerance of the determination of soil-moisture contents. The moisture dropped from about 16.25 inches to about 6.4 without becoming concave upward as would be the case if transpiration decreased with decreasing soil moisture. This is about 92 pct of the total range of 16.25 to 5.5 inches. It also should be noted that the San Dimas area was blanketed with fog for days at a time during May and June. This, of course, should have lessened transpiration markedly at this time.

Colman, while admitting that transpiration will not be influenced by the moisture well within the available range of soil moisture, repeatedly raises the point that it may do so at the permanent-wilting percentage. Our experiments show that transpiration is independent of soil moisture until the soil is reduced to the permanent wilting percentage as closely as can be measured by the means available.

Van Bavel's comments are similar to those of Colman in that he questions whether the soil moisture can be reduced exactly to the permanent wilting percentage without decreasing the rate of transpiration. Our discussion of Colman's comments applies to Van Bavel's in this respect. Van Bavel states, referring to Figures 4, 5, and 6, that there is a gradual decrease of the slope of the lines when these are approaching the wilting percentage. This statement may be questioned. The changes in rates of transpiration occur within about a half per cent of the permanent wilting percentage. This is within the range of determination of the value for this moisture condition for fine textured soils.

Van Bavel suggests that the data would be more conclusive if adjacent areas with high and low moisture content could be compared during the same time period. Such a comparison can be made from the data in Tables 2 and 3. Plots were chosen from an irrigation experiment with prunes and with grapes so that one had a higher initial moisture content than the other. Both were then left unirrigated for a long period. Those in Table 2 are from a prune orchard at Davis. The soil was about as uniform as could be expected. The moisture equivalents and permanent wilting percentages at the bottom of the table show fairly good agreement. There were three samples from each of three rows so that each soil moisture value is the average of nine determinations.

Both treatments showed a gradual reduction in average moisture contents as the season progressed. In general, the moisture contents in D were lower than those in E. At the end of the sampling period on July 31 the moisture contents in D were at or near the permanent wilting percentage while those in E were slightly above this value except in the top foot. The losses due to transpiration were essentially equal in both plots period by period and showed that a reduction in soil moisture to about the permanent wilting percentage did not cause a decrease in transpiration.

A further sample of this fact is evidenced by the data in Table 3 taken from a vineyard at Davis. The moisture equivalents and permanent wilting percentages given in the table are the averages for the entire vineyard. The soil moisture was reduced close to the permanent wilting percentage in all depths except the three to four-foot depth in row 7 on July 15, while that in row 16 was above the permanent wilting percentage in all depths of soil. The moisture content, furthermore, in the top two feet of soil in row 7 was at the permanent wilting percentage on July 1. Here, again, transpiration does not decrease as soil moisture decreases.

Table 2--Soil moisture percentages and losses in moisture in a prune orchard for successive periods, depth 0-6 feet

Date	Treatment E					Treatment D				
	Moisture	ΔLoss	ΣLoss	ME[a]	PWP[b]	Moisture	ΔLoss	ΣLoss	ME[a]	PWP[b]
	pct	pct	pct	pct	pct	pct	pct	pct	pct	pct
Apr. 24	22.5	...	...	21.7	9.1	20.7	...	...	20.2	9.2
May 13	19.8	2.7	2.7			18.0	2.7	2.7		
May 28	18.1	1.7	4.4			16.4	1.6	4.3		
June 10	16.4	1.7	6.1			15.1	1.3	5.6		
June 24	14.3	2.1	8.2			12.8	2.3	7.9		
July 8	13.6	0.7	8.9			11.2	1.6	9.5		
July 31	10.4	3.2	12.1			8.7	2.5	12.0		

[a] ME = Moisture equivalent. [b] PWP = Permanent wilting percentage.

Table 3--Soil moisture percentages and losses in moisture in a vineyard for successive periods, depth 0-6 feet

Date	Row 16					Row 7		
	Moisture	ΔLoss	ΣLoss	ME[a]	PWP[b]	Moisture	ΔLoss	ΣLoss
	pct	pct	pct	pct	pct	pct	pct	pct
June 5	18.6	...	...	18.2	10.0	15.3	...	...
July 1	15.1	3.5	3.5			12.0	3.3	3.3
July 15	13.3	1.8	5.3			10.6	1.4	4.7

[a] ME = Moisture equivalent. [b] PWP = Permanent wilting percentage.

The data illustrated in Figure 1 also will serve to answer Van Bavel's question. The climatic conditions in California for two successive days, just before and immediately after irrigation, are near enough alike to indicate whether soil moisture influences transpiration. In no case do the data in the figure suggest that decreasing soil moisture causes a decrease in transpiration.

Mech suggests that transpiration be shown on a daily basis. The data in Figure 1 are daily records. Further examples of daily records of transpiration follow. That from sunflower plants in buckets holding about ten quarts of soil is shown in Table 4. The surface of the soil was sealed to prevent evaporation losses. The plants were grown in a greenhouse. The transpiration is given for a 12-hour period together with the soil moisture at different times during the day. These results are typical for a number of days during which similar tests were made. Transpiration by sunflowers in buckets grown in the greenhouse plotted against soil moisture for a period July 4 to July 7 is shown in Figure 10. Although the soil moisture was reduced close to the permanent wilting percentage in some cases, the plants were not allowed to wilt. There is no correlation between soil moisture and transpiration. A typical example of our results with sunflowers in small containers is shown in Figure 2. This plant was grown in the laboratory under approximately constant evaporative conditions.

Further tests, with bean plants in small cans holding about 600 gm of soil, were made by growing the plants in a constant-temperature room under artifical illumination. Here evaporation conditions were remarkably constant. The leaf surface on each plant was measured about every second day and the results are given in Tables 5 and 6 for the transpiration for each 100 cm^2 of leaf surface per hour averaged for each day. The average soil moisture for the day is also listed. There were two sets of experiments: one in which the plants were allowed to go from five to six days (Table 5) before irrigating and the other from nine to ten days (Table 6) before applying water. The plants for the record in Table 6 were carried up to the time just before wilting occurred. They were rewatered in most cases and the transpiration was again measured. The plants reported in Table 5 in some cases were irrigated again after the sixth day.

Table 4--Transpiration by sunflower plants in ten-quart buckets in greenhouse, grams per 100 cm^2 of leaf surface, 06h - 18h, and soil moisture percentages during this period, on July 5, 1952

Plant	Leaf surface	Soil moisture percentage hour							Transpiration per 100 cm^2 leaf surface
		06	10	12	14	16	18	Aver.	
	cm2	pct	pct	pct	pct	pct	pct	pct	gm
226	872	31.9	31.6	30.9	30.0	29.1	28.6	30.3	30.90
202	842	30.6	30.3	29.7	29.0	28.2	27.8	29.3	26.93
220	774	28.9	28.6	27.9	26.8	26.2	25.8	27.4	32.97
242	979	28.0	27.6	26.8	25.7	24.7	24.2	26.2	31.86
219	974	28.0	27.6	26.7	25.7	24.6	24.1	26.1	33.45
222	1353	28.0	27.4	26.2	24.8	23.8	23.8	25.6	28.26
247	601	27.1	26.7	26.2	25.5	24.8	24.5	25.8	35.38
223	630	26.7	25.8	25.3	24.6	23.9	23.5	25.0	33.74
227	971	25.8	25.5	24.6	23.4	22.3	21.8	23.9	33.62
225	703	24.7	24.3	23.5	22.6	21.7	21.2	23.0	40.38
228	716	24.4	23.9	23.2	22.3	21.4	20.9	22.7	39.58
235	690	24.3	24.0	23.3	22.2	21.7	21.2	22.8	37.00
239	822	24.0	23.5	22.8	21.7	21.0	20.5	22.2	33.98
246	619	23.2	22.8	22.1	21.2	20.7	20.2	21.7	38.92
224	453	23.1	22.6	22.2	21.6	21.2	20.9	21.9	40.71
215	476	21.5	21.1	20.6	19.9	19.6	19.2	20.3	38.71
244	552	20.8	20.4	19.9	19.4	19.0	18.7	19.7	30.97

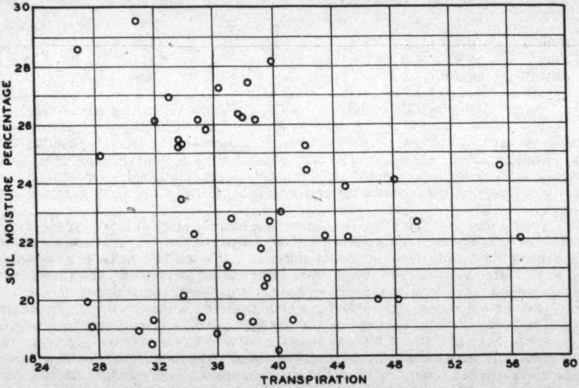

Fig. 10--Transpiration by sunflower plants grown in ten-quart buckets; the surface was sealed over to prevent evaporation; the transpiration is in gm/100cm^2 of leaf surface per day; the record is for the period July 4 - 7, 1952; The soil moisture percentages in the various buckets varied from about 30 to 18 pct

In working with plants in containers, we have found it is necessary to grow the plants long enough to insure a thorough permeation of the soil with the roots. Unless this is done, it may sometimes appear that there is a decrease of transpiration with decrease in soil moisture if the average soil moisture is calculated from the weight of the can and its contents. We always let the plant wilt at least once to insure complete root penetration before starting the test. Sometimes, if the wilting is severe, root injury may result and the rates of transpiration following irrigation may be lowered. To avoid this possibility, the rates on the first day following watering are not listed.

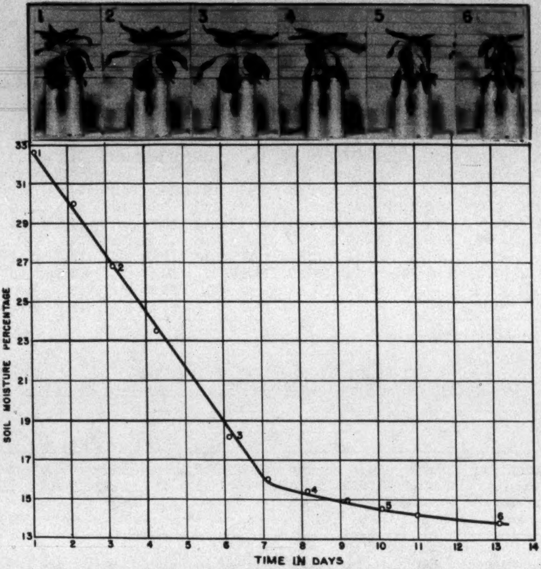

Fig. 11--Transpiration by a sunflower plant in a sealed can with about 600 grams of soil under approximately constant environment; the photographs were taken at the time indicated by the numbers

Table 5--Soil moisture and transpiration in grams per 100 cm^2 of leaf surface of bean plants per hour

Plant	Days after irrigation									
	2		3		4		5		6	
	M[a]	T[b]	M	T	M	T	M	T	M	T
	pct	gm	pct	gm	pct	gm	pct	gm	pct	gm
50	20.6	0.11	19.6	0.10	18.3	0.11	18.0	0.13	16.2	0.12
50	20.5	0.12	19.2	0.12	18.2	0.12	16.9	0.13	...	...
49	21.2	0.14	20.6	0.13	19.0	0.13	18.1	0.14	16.9	0.14
48	20.2	0.11	19.2	0.11	18.1	0.10	17.3	0.12	16.1	0.12
47	19.7	0.13	18.5	0.12	17.4	0.12	16.5	0.13	15.3	0.12
46	20.8	0.10	19.8	0.10	18.9	0.10	18.1	0.11	17.0	0.11
32	21.1	0.14	20.1	0.15	18.7	0.14	17.7	0.13	...	...
32	20.1	0.10	19.1	0.10	17.8	0.10	16.8	0.12	15.7	0.14
31	20.1	0.13	18.6	0.13	17.5	0.14	15.9	0.14	...	...
30	21.0	0.15	20.2	0.16	18.8	0.16	17.7	0.17	16.6	0.17
29	21.7	0.12	20.7	0.11	19.6	0.11	18.6	0.12	17.5	0.12
27	21.7	0.12	20.7	0.11	19.6	0.11	18.6	0.12	17.5	0.12
26	21.4	0.11	20.6	0.12	19.8	0.12	19.1	0.12	18.2	0.13

[a] Moisture [b] Transpiration

Transpiration rates in Table 5 are about the same as those in Table 6 even though the plants in the former were irrigated to keep the soil moisture from falling below about 16 pct and those in the latter were allowed to drop to about 11 pct.

A summary of the results of the tests reported in Tables 5 and 6 is given in Table 7 to show the variability in the data for the soil moisture contents and the standard errors for the transpiration data. The differences between transpiration at the different moisture levels are not significant.

Table 6--Soil moisture and transpiration in grams per 100 cm^2 of leaf surface of bean plants per hour

Plant	Days after irrigation													
	2		3		4		6		8		9		10	
	M[a]	T[b]	M	T	M	T	M	T	M	T	M	T	M	T
	pct	gm	pct	gm	pct	gm	pct	gm	pct	gm	pct	gm	pct	gm
40	...	...	18.6	0.09	17.6	0.10	15.7	0.10	13.5	0.11	12.3	0.11	11.5	0.10
39	21.7	0.13	20.0	0.13	19.2	0.11	17.3	0.12	15.4	0.13	14.2	0.13	...	...
39	...	...	...	...	18.6	0.09	16.7	0.11	14.9	0.10	14.3	0.09	13.3	0.09
38	19.0	0.10	18.2	0.10	17.3	0.10	15.7	0.12	13.5	0.12	12.7	0.12	11.7	0.11
38	21.9	0.14	20.8	0.14	19.6	0.11	17.6	0.12	15.7	0.14	14.5	0.14	13.7	0.11
37	...	...	18.9	0.12	18.1	0.12	15.9	0.12	13.7	0.13	...	...	...	...
37	...	...	...	...	17.3	0.13	15.7	0.13	13.7	0.13	12.7	0.12	12.0	0.12
36	21.5	0.12	19.7	0.13	18.9	0.12	16.8	0.12	14.4	0.13	13.3	0.10	12.3	0.11
36	...	...	...	...	17.1	0.11	15.4	0.12	13.5	0.11	12.2	0.10	11.4	0.11
35	20.1	0.10	19.0	0.10	17.9	0.11	15.8	0.11	13.8	0.11	12.8	0.11	11.6	0.10

[a] Moisture. [b] Transpiration.

Table 7--Average transpiration in grams per 100 cm^2 of leaf surface of bean plants per hour and average soil moisture percentage

Item	Days after irrigation								
	2	3	4	5	6	7	8	9	10
Transpiration, gm	0.120	0.118	0.116	0.122	0.123	0.122	0.121	0.114	0.106
[Standard error	±.0037	±.0039	±.0031	±.0031	±.0033	±.0043	±.0036	±.0052	±.0323
Aver. soil moisture for the day, pct	20.8	19.6	18.4	17.4	16.5	15.2	14.2	13.2	12.2

Mech discusses his 'consumptive use' data and seems to think that they indicate greater use of water by plants with high soil moisture than by ones with low moisture. If drainage is included in the consumptive use measurements, of course they will increase with the frequency of irrigation, but this does not mean that transpiration also will be increased.

Stoltenberg mentions the effect varying environmental conditions may have on transpiration. Attention is called to the data in Tables 5 and 6 of this discussion which were obtained under controlled temperature, light and humidity conditions. He refers to the work of WADLEIGH and GAUCH [1948]. Figure 4 of their paper shows soil moisture curves to have uniform slopes indicating about the same ratio of transpiration throughout the range of moisture through which the soil was allowed to fluctuate. Figure 1 of the paper by BLAIR, RICHARDS and CAMPBELL [1950] shows wide ranges in soil moisture with uniform rates of extraction.

While the small size of the jars used by HAYNES [1948] to grow his corn plants may be an important factor in the results he obtained, he did conclude that transpiration per unit of dry matter produced was not affected by variation in soil moisture from near saturation to near the permanent wilting percentage.

Stoltenberg calls attention to the extension of roots into the soil. Doneen also discussed this matter in considerable detail. We believe this is an important consideration in interpreting the results of soil moisture studies. We have used permanently rooted tree crops in most of our investigations to avoid the difficulties which arise from poor or sparsely developed root systems.

Mather's comment that we say that container experiments should not be taken as conclusive is not correct. We did say that field trials were preferable to container experiments. Mather's reference to his evapotranspirometer tanks indicates that he places confidence in container experiments. It is not clear how he can make a comparison between transpiration and soil moisture with no determination of soil-moisture contents. Furthermore, with the waterlogged conditions in some of his tanks, evaporation may have been a large part of the amount he reports as evapotranspiration. The amount of evaporation from the soil surface may be markedly different in the waterlogged tanks than that from the drained ones.

Mather's a priori reasoning in Figure 8 does not necessarily mean that the rates of transpiration would be as he has indicated them. The rate of use in Figure 6 is higher from the middle of June to the middle of July than for any other time. At the end of July the soil moisture was at about the permanent wilting percentage. If samples had been obtained a few days earlier, it is very probable that the slope of the extraction curve would have been at least as steep as for the previous period between samplings.

Figure 4 illustrates this fact very clearly. The average loss from the soil profile shows a marked increase from the sampling in the last week in June to that in July when the moisture supply was exhausted. Figures 1 and 2 permit comparisons to be made of the transpiration at high and low soil moisture contents under about the same evaporation conditions. The data in Tables 2-6 afford the same opportunity. The data in Tables 5 and 6 were obtained by growing the bean plants under constant light, temperature, and humidity conditions. They all show that transpiration is not decreased as soil moisture decreases.

Mather refers to the work of Soviet scientists who think that optimum soil moisture for plant growth is high in the range of availability. We only have the translation of one Russian work, that by KOKIN [1925] who concludes from her studies with various kinds of plants in containers that 'No direct ratio exists between the water content of the soil and the transpiration of water by the plant. The fluctuation of the moisture content of the soil through wide ranges does not exhibit any influence on the velocity of the intake of water by the root system.'

Taylor's theoretical discussion of transpiration of two identical plants at different soil-moisture contents leads us to believe that he thinks the transpiration will be the same for both plants. However, from the data for alfalfa, sugar beets, and potatoes used in his experiments, he states that the use of water was higher from the soils which were moist longest than in dryer ones. We would like to know whether the moisture in the latter case was reduced to the permanent wilting percentage in any depth of soil.

Lassen, Lull, and Frank ask why we reason the resistance to removal of water by the plant would become effective at the permanent wilting percentage. The position of the permanent wilting percentage on the soil-moisture energy curve clearly indicates why this should be true.

Lassen, Lull, and Frank seem to discourage the use of empirical data, but use them in Figure 9. We have no way of knowing whether their soil is at field capacity, the permanent wilting percentage, or whether it is saturated. The very high moisture contents given for six inches of soil would indicate the soil was saturated. There is no indication of rains. It is very probable that drainage was largely responsible for the shape of the curves in Figure 9. Certainly these data are not convincing in answering the question we posed. A condition propitious for studying moisture extraction in the field is deep soil with long periods between rains or irrigation.

The increase in the weight of the tree in Figure 1 is so small it could not have affected the results. In fact, the total weight of the tree after growing in the tank for about four years would not have changed the calculated soil moisture. The tree and branches weighed 3.5 lb and the roots 4.5 lb. It was planted on April 15, 1919, and taken out of the tank January 30, 1923. The weight of the leaves is not known, but it was much less than the weight of the wood. Assuming there were six months growing season each year, there would be 720 days during which the tree would be growing. If we assume the weight of leaves equaled the weight of the tree at planting time, then the daily increase in weight would be about 0.011 lb. This weight on the 1000 lb of soil in the tank would be about 0.001 pct per day. The pine tree in Figure 2 weighed, 1547 days after it was planted, 50 lb with 11.8 lb of needles, a total of 61.8 lb. Assuming one-half of the days were growing ones, we can calculate the increase in daily weight of 0.08 lb. This amounts to 0.0032 pct soil moisture on the 2500 lb of soil in the tank. Certainly the daily comparisons of transpiration or even weekly ones are not distorted by the effect of increase in weight of the plant.

The tanks (Figs. 1 and 2) were placed in outer ones partially filled with water and were shaded. The surface of the soil in the tanks was about at the level of the surrounding ground. The temperature of the soil in the tanks was about the same as in the field. The temperature factor, therefore, is unimportant in this case and cannot be used to vitiate our results.

Lassen, Lull, and Frank's statement that our moisture extraction curves show definite evidence of curvilinearity is not correct. Certainly they are not concave upward as would be the case if decreasing soil moisture resulted in decreasing transpiration. Of course, there are some instances in the curves we have published where there is a steepening of the curves especially in the top foot of soil following irrigation or rains, due to drainage and to surface evaporation. The decrease in slope of some of our curves during the latter part of the growing season obviously is due to defoliation and lessened evaporating conditions.

It is difficult to evaluate Lassen, Lull, and Frank's comment concerning the fact that the greatest drop in energy occurs at the leaf surface. We cited the fact to show that the resistance offered by the plant in the soil-plant-water system is relatively unimportant and that until the permanent wilting percentage is reached, there always is a differential in favor of the atmosphere to take water from the plant, a point which Woodruff also emphasizes.

Kramer refers to the work of ARMY and KOZLOWSKI [1951]. The only transpiration data they present were for four-hour periods with plants in solutions with various concentrations. It is very probable that this was too short a time to allow the plants to become adjusted to the high concentrations. We have found that plants transferred to relatively high concentrated solutions from lower ones take considerable time before they have accumulated enough material in the absorbing portions of the roots to balance the osmotic value of the solution in which they are placed.

KOZLOWSKI [1949] is referred to by Kramer as showing that photosynthesis decreases with decreasing soil moisture. BURNS [1926], working with forest trees, states, 'Decreases in moisture content did not decrease photosynthesis activity until the former reached its minimum and death occurred for lack of water.' ALLMENDINGER and Others [1943] state that carbon dioxide intake is uniform throughout a wide range of soil moisture from about 37 to approximately ten per cent. They report the wilting point of their soil to be seven per cent. The difference in average intake of the gas for the entire period of observation does not seem to be significant for the three trees in which all the readily available water was utilized and for those of the other treatments.

UPCHURCH [1952] studying ladino clover at Davis found, 'No reduction in photosynthetic activity was noted until the approximate time of appearance of the first sign of wilting.'

KOZLOWSKI [1949] shows photographs of trees used in his experiments (Figs. 5 and 6) for two moisture treatments. He states that the soil in his dry treatment was allowed to dry down practically to the wilting percentage before it was rewatered to the field capacity. These roots, he says, were exposed to rather severe drought several times during one growing season. It is to be expected, then, that these trees would be affected adversely, and confidence in his conclusions is lessened.

Kramer refers to the work of CLEMENTS [1948] and states there is increasing evidence that maintenance of soil moisture near field capacity is desirable for maximum vegetative growth of at least some crops. But SHAW [1930], WADSWORTH [1932, 1934, 1941], SHAW and SWEZEY [1937], and BORDEN [1948] show that soil moisture may fluctuate throughout the range of readily available moisture without reducing growth of cane or yield of sugar. CLEMENTS and Others, [1952] state that the field capacity of the soil at Waipo ranged from 35-37 pct. Its wilting point is said to be 24-25 pct and that whenever the soil moisture dropped below 28 pct there was a check in growth. This is a range in readily available water of 11-12 pct, a relatively wide range for Hawaiian soils. But SWEZEY [1942], also working at Waipo at the same experimental station, gives the field capacity as 36 pct and the first permanent wilting percentage as 28 pct. Swezey states, 'A reduction of cane tonnage resulted from repeatedly withholding irrigation until some time after the 'permanent wilting percentage was passed', but there was no commercial loss, since the sugar yield was not reduced.' The statement of CLEMENTS and Others [1952] based on the data in Figure 21 of their report may be questioned on another count. Here he has plotted daily growth rates against soil moisture, but the data were taken at different times during the year when climatic conditions may have been markedly different for growth. In other words, he does not compare the growth at high moisture content with that at a lower one on the same day or possibly under the same growth conditions.

Kramer fails to note that we point out in our article on apricot irrigation [HENDRICKSON and VEIHMEYER, 1951] that the trees which showed a decrease in cross-section area in comparison with those which did not reach the permanent wilting percentage, were subjected to various periods of drought when the soil moisture at least in the top three feet was reduced to the permanent wilting percentage. This lack of readily available moisture was not enough to reduce yields significantly but it did reduce growth of the trees. We should mention that others, in criticizing our work, have called attention to the same comparisons as Kramer does, not only for apricots but for other kinds of fruit trees with which we have worked, but in every case where there has been a lessening of growth, it occurred only when a relatively large portion of the soil has been reduced to the permanent wilting percentage and remains there for an appreciable period of time. If the soil moisture reaches the permanent wilting percentage, but is not allowed to stay there, growth has not been affected adversely.

Length of growth on deciduous fruit trees in California may cease in mid-June before the water stored in the soil from the winter rains is exhausted. Growth of fruit, depending upon the species, may continue into August. Fruit growth is very sensitive to the lack of readily available water and will evidence this by slowing of growth while shoot growth would show nothing since it ceased while there still was readily available water in the soil. We have repeatedly shown the reduction of fruit growth to be coincident with the time the moisture is reduced to the permanent wilting percentage, but that the rate of growth of the fruit is not influenced by different amounts of readily available water in the soil.

Kramer says that theoretically water cannot be equally available over the range from field capacity to the permanent wilting percentage because this covers a DPD range from zero to 15 atmospheres in the soil. This statement is open to question. We have shown [VEIHMEYER and HENDRICKSON, 1949] that sugar beets and sunflower plants can take water from 16-atmosphere solutions. The fact that the 'evaporating power' of the air is many times the 15-atmosphere value Kramer mentions supports our statement rather than his. Furthermore, the much larger amount of energy required to evaporate water from the leaf tissues than that used in taking water from the soil even when at the permanent wilting percentage and transporting it to the leaf indicates that the slight increase in resistance from soil to plant may be unimportant until the resistance to removal of the water from the soil increases markedly as the soil moisture is reduced slightly below the permanent wilting percentage.

Wilting of plants in the field under very high evaporation rates when the soil may be above the permanent wilting percentage may be due to the resistance offered to the entrance and passage of water through the plant. Wilting of plants grown in dilute nutrient solutions which can be induced by subjecting them to high evaporating rates surely is due to resistance offered by the plant and not because of the inability of the solution surrounding the roots to deliver water to them. GARDNER [1944], after discussing the energy relations of evaporation and soil moisture, suggests that 'wilting may be due to the slow movement of the water into the plant from a dry soil and not to the excessive amount of energy required to remove it from the high-tension moisture.' But, as we have stated previously, the relation of transpiration and soil moisture cannot be decided by a priori reasoning, but must be settled by empirical trials.

Kramer states that it has been adequately demonstrated that water uptake and plant growth are often reduced by soil moisture tensions or DPD's of from one to four atmospheres. We have reviewed [VEIHMEYER and HENDRICKSON, 1950] many of the principal articles published on this subject and we believe that the following conclusion we reached is justified. 'The results of investigation on the relation of plant growth to soil moisture show that the plants grow well throughout a wide range of soil moisture, but some investigators question whether they do so with equal facility throughout the entire range from field capacity to the permanent wilting percentage. The permanent wilting percentage is the most important soil-moisture constant. The accuracy of its determination is highly important.'

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SOUTHWEST PACIFIC CRUSTAL STRUCTURE

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(Woods Hole Oceanographic Institution Contribution No. 724)

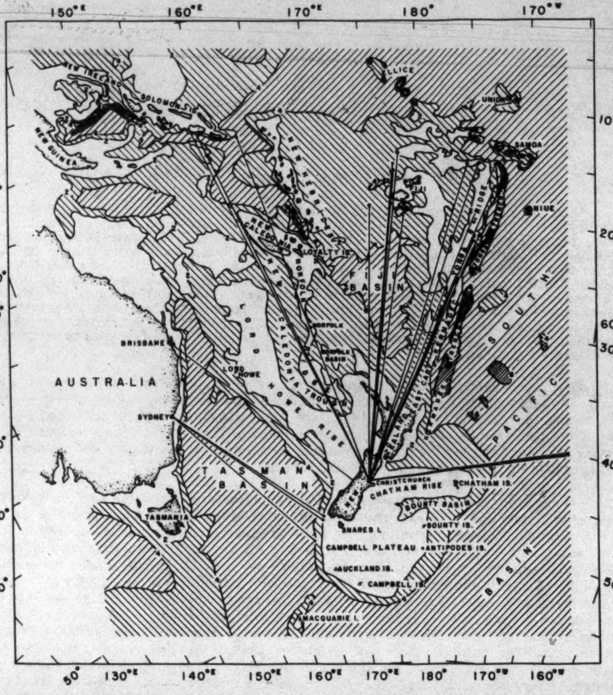
Abstract--This investigation has been concerned with the determination of the crustal thicknesses of the various features of the Southwest Pacific from Love- and Rayleigh-wave dispersion characteristics. The crustal thickness of the Tasman Basin between New Zealand and Australia is the same, five to ten km, as that for the South Pacific Basin to the east of New Zealand. The thickness of East Cape - Kermadec - Tonga Ridge bordering the South Pacific Basin on the west and that of the Lord Howe Rise bordering the Tasman on the northeast is 20-25 km. A crustal refraction profile over New Zealand gives a thickness of 20 km. The interior region of ridges and troughs, northeast of New Zealand, has an average thickness of 15-20 km. The results are indicative of an origin from successive orogenic belts built out over an oceanic crust. The area is not part of an extensive continent.

Introduction--Recently the author has had the opportunity to be in New Zealand on a Fulbright research fellowship and to be able to examine the crustal structure of the Southwest Pacific from the New Zealand network of stations and from the Australia stations at Brisbane and Sydney. The purpose of the research has been to determine the crustal thicknesses of the various features in this rather complex area for the conclusions that they might add to its geologic history and to a general knowledge of the geology of suboceanic areas.

The method used was to examine the dispersive characteristics of the surface wave trains from selected distant earthquakes. These waves travel in the wave guide bounded at the bottom by the familiar Mohorovicic discontinuity. This boundary represents a discontinuity in seismic velocity from a value of 6.5-7.0 km/sec to a value of 8.1 km/sec. It is a datum which has been observed from both earthquake and explosion seismology over the Earth. Under the continents, it is at a depth of 35 to 60 km being deepest under the high mountain ranges. Under all explored ocean-basin areas, it is at a depth of 10 to 13 km below sea level. This shallow depth is found uniformly under all ocean basin areas and is a distinguishing feature of these areas, indicative of their stability and their lack of direct association in the geosynclinal and resultant tectonic activities in the past. The seismic velocity of the material below this discontinuity is higher than measured on surface rocks; it is probably ultrabasic [HESS, 1954], the exact nature of the physical or chemical change across the discontinuity remaining a question to be answered. That such material has taken part in tectonic activity is evinced by its depression under the mountain ranges, but that it represents the depth of isostatic compensation, as has been considered by some, is doubtful. In this paper it is used in the seismic sense only to distinguish between areas of thin crust, 5-10 km, typical of the ocean basins and those of thick crust, 35-60 km, typical of the continents and to determine the thickness under the active geologic regions of the island arcs.

Previous investigations have been limited for the most part to the determination of the crust under New Zealand. HAYES [1935], BULLEN [1936; 1939], and EIBY [1949] have obtained results from travel time curves for local earthquakes. In addition, E. I. Robertson and the staff of the New Zealand Geophysics Division made a crustal refraction profile on a line northeast from Wellington. DE JERSEY [1946] studied Rayleigh waves recorded at Brisbane from the Solomons, Samoa, and the Kermadecs.

Figure 1 is a bathymetric map of the Southwest Pacific with the earthquake paths that were used. The nomenclature is that of BRODIE [1952]. To the east is the broad expanse of the South Pacific Basin extending over to the Easter Island Rise. Between New Zealand and Australia there is an extension of this deep water area in the Tasman Basin. Bordering the South Pacific Basin is the sequence of the Kermadec and Tonga Trenches and the East Cape - Kermadec - Tonga Ridge extending from New Zealand to Samoa. The major belt of shallow-focus earthquakes, not shown, follows along the eastern side of the Ridge with the intermediate and deep focus belts along the same trend further to the west. This sequence appears again in the New Hebrides and Solomons


150°E
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NEW IRELAND
SOLOMON IS.
NEW GUINEA
ELLICE
UNION
SAMOA
NIUE
NEW HEBRIDES
NEW CALEDONIA
LOYALTY IS.
FIJI
FIJI BASIN
TONGA RIDGE
NORFOLK
NORFOLK BASIN
BRISBANE
LORD HOWE
LORD HOWE RISE
NEW CALEDONIA TROUGH
AUSTRALIA
SYDNEY
TASMAN BASIN
TASMANIA
NEW ZEALAND
EAST CAPE
KERMADEC
CHRISTCHURCH
CHATHAM RISE
CHATHAM IS.
BOUNTY BASIN
BOUNTY IS.
SNARES I.
CAMPBELL PLATEAU
ANTIPODES IS.
AUCKLAND IS.
CAMPBELL IS.
MACQUARIE I.
SOUTH PACIFIC BASIN

Fig. 1--Bathymetric chart of the Southwest Pacific including earthquake paths

with the trenches now on the side away from the Pacific Basin. Between these two is the Fiji area and the Fiji Basin. Bordering the Tasman Basin on the northeast is the Lord Howe Rise. Further to the northeast are the New Caledonia Trough, Norfolk Ridge, and Norfolk Basin.

For the South Pacific Basin earthquakes from the Easter Island region recorded at Christchurch were used. For the Tasman Basin the travel path was fairly short, and it was advantageous to pick earthquakes and a station for which no correction would be needed for travel through a different structure. Earthquakes off the southwest of New Zealand to the Riverview station, Sydney, met this requirement. No earthquake paths were available to the station at Samoa for the investigation of the crust under the Kermadec and Tonga Trenches. For the East Cape - Kermadec - Tonga Ridge earthquakes from Samoa and Tonga recorded at Christchurch were used. Fortunately the composite thickness along the whole path was the same as that found from the local earthquake studies and the crustal refraction profile for New Zealand so that no correction was necessary. For the Lord Howe Rise two earthquakes from New Zealand to Brisbane along the edge of the Rise were available. For the interior region a composite thickness was obtained along paths from the Solomons to Christchurch. For the Fiji Basin earthquakes from the Fiji area to Christchurch were used. A correction was made for the portion of the path across New Zealand and Fiji in order to determine the thickness of the crust under the Fiji Basin.

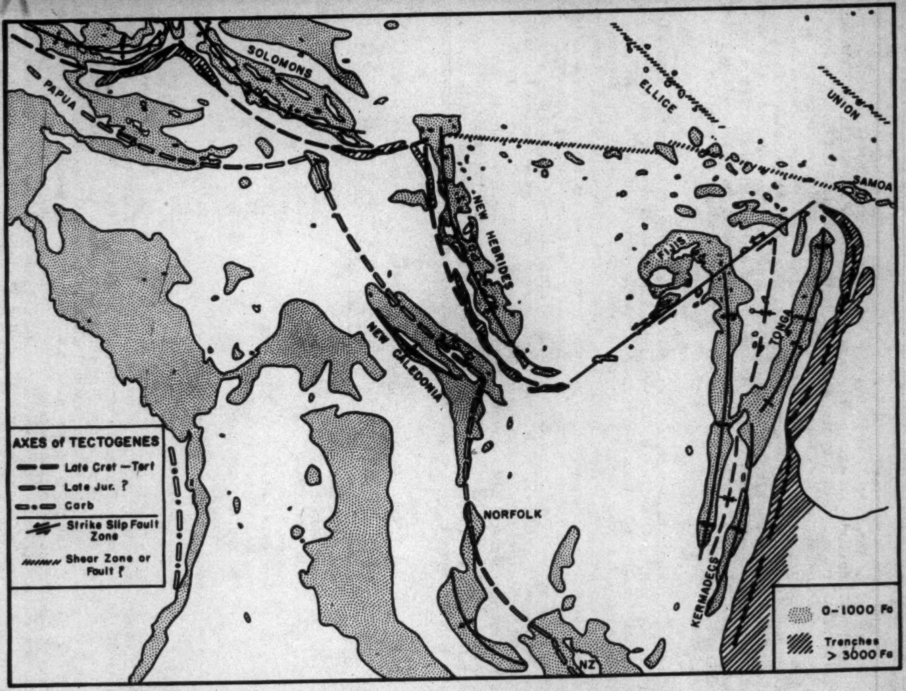

SOLOMONS
PAPUA
ELLICE
UNION
SAMOA
NEW HEBRIDES
FIJIS
TONGA
NEW CALEDONIA
NORFOLK
KERMADECS
NZ
AXES of TECTOGENES
Late Cret —Tert
Late Jur. ?
Carb
Strike Slip Fault Zone
Shear Zone or Fault ?
0-1000 Fa
Trenches > 3000 Fa

Fig. 2--Summary of the geology of the region according to HESS and MAXWELL [1949]

The regional geology is summarized in Figure 2, taken from a paper by HESS and MAXWELL [1949]. Five orogenic belts are recognizable. The first of Precambrian age extends north-south across Western Australia. The second of late Ordovician age extends from Melbourne toward Cape York. The third of late Paleozoic age, shown in Figure 2, is in the vicinity of Brisbane. A fourth of probable late Jurassic age is found along the inner island arcs from New Guinea and the Louisades, New Caledonia, and the western margin of New Zealand. The fifth and presently active belt follows the outer island arcs from New Britain, the Solomons, to the New Hebrides, then offset to Tonga and the Kermadecs. The geology of New Zealand is summarized in the geologic map of the North and South Islands and accompanying pamphlet by the NEW ZEALAND GEOLOGICAL SURVEY [1947; 1948] and in a memoir by MacPHERSON [1946]. The orogenic belt from Tonga and the Kermadecs is continued along the eastern margin of the North Island in the northeast trending Cretaceous and Tertiary geosynclinal deposits, the extension of the Kermadec Trench at shallower depth offshore from the North Island, and the zones of shallow, intermediate, and deep focus earthquakes. Cretaceous and thick Tertiary deposits are also present on the western side of the North Island along the northwest trend of the older orogenic belt of the inner island arcs. The region between these two converging belts is a volcanic plateau traversed by the Taupo - Rotorua graben. GLAESSNER [1952] and GILL [1952] have recently summarized two views on the geology of the Tasman Basin.

Theory--Surface waves from shallow focus earthquakes are the guided waves which have been propagated by multiple reflection in the Earth's crust. The net effect of adding up the mutual interferences of the multiple reflections is to produce a dispersive wave train, that is, a wave train in which the observed frequency changes in a regular manner with time of arrival. The dispersive characteristics depend upon the physical constants of the crust and subcrust and the thickness of the crust. Two types of surface waves are possible. In one, Love waves, the particle motion is transverse to the direction of propagation and polarized parallel to the reflecting boundary. In the other, Rayleigh waves, the particle motion is retrograde elliptical in the direction of propagation. These differences in the types of particle motion for Love and Rayleigh waves and the fact that Love waves travel faster than Rayleigh waves allow one to identify the two trains separately and read the dispersive characteristics of each. The theory of surface waves has been given by several authors and will not be repeated here. A recent contribution has been made by EWING and PRESS [1950; 1952] in the recognition that the observed Rayleigh waves across oceanic areas travel in the combined wave guide of ocean and crust whereas the Love waves, being a shear vibration, are confined to the crust.

Table 1--Crustal thicknesses

Area	Crustal thickness
	km
North Pacific Basin	5
South Pacific Basin	10, 5-10
Tasman Basin	5-10, 10
East Cape - Kermadec - Tonga Ridge	25
New Zealand (refraction profile)	20
New Zealand (earthquakes)	20-30
Lord Howe Rise	20
Solomons to New Zealand	15-20
Fiji Basin	15

The practice here will be to compare the experimental results with a single layered crust of constant velocity underlain by subcrust of different velocity to arrive at a value for the thickness of the crust. For both surface waves theoretical curves were calculated for two crustal velocities, one lower than the average velocity obtained from earthquake and crustal refraction profiles elsewhere and the other higher. The values given in Table 1 for the crustal thicknesses are a mean of these two curves. The velocity of P_n was taken as 8.1 km/sec for all cases. This graphical method has been chosen to compare the experimental results with theory so that the reader may judge for himself how well the thicknesses have been determined and what variations in thickness would be realized on the assumption of different crustal velocities. A change in the subcrustal structure, P_n, which is a definite possibility for the disturbed areas of the island arcs, will alter the thicknesses quoted in Table 1 but will not change the general conclusion for the structure of the area.

The theoretical curves for Love waves were calculated for two values of α_1, using α_2 as constant: $\alpha_1 = 6.50$ km/sec, $\beta_1 = 3.65$, $\alpha_2 = 8.10$, $\beta_2 = 4.55$, $\rho_2/\rho_1 = 3.00/2.67$; and $\alpha_1 = 6.05$ km/sec,

$\beta_1 = 3.40$, $\alpha_2 = 8.10$, $\beta_2 = 4.55$, $\rho_2/\rho_1 = 3.00/2.67$; where α and β are the P and S velocities, and ρ the density as shown in Figure 3. A value of $\sigma = 0.27$ was taken for Poisson's ratio for this range of velocities. Following JARDETSKY and PRESS [1953] Rayleigh waves were calculated for the two cases: $\alpha_0 = 1.52$ km/sec, $\alpha_1 = 6.90$, $\beta_1 = 3.98$, $\alpha_2 = 8.10$, $\beta_2 = 4.68$, $\rho_1/\rho_0 = 2.67$, $\rho_2/\rho_0 = 3.00$; and $\alpha_0 = 1.52$ km/sec, $\alpha_1 = 5.50$, $\beta_1 = 3.18$, $\alpha_2 = 8.10$, $\beta_2 = 4.68$, $\rho_1/\rho_0 = 2.67$, $\rho_2/\rho_0 = 3.00$. For ease in calculation Cauchy's value of $\sigma = 0.25$ was taken for Poisson's ratio. Jardetsky and Press calculated the Rayleigh wave dispersion curves for these two cases for $H = H_0$. For this investigation it was necessary to extend the calculations to ratios $H = 2H_0$, $5H_0$, and $10H_0$. These calculations are fairly laborious and are given in Table 2 in dimensionless form for the use they may be to other investigators. The period T is related to kH_0 by $T = 2\pi H_0/(kH_0)C$. C is the phase velocity and U the group velocity.

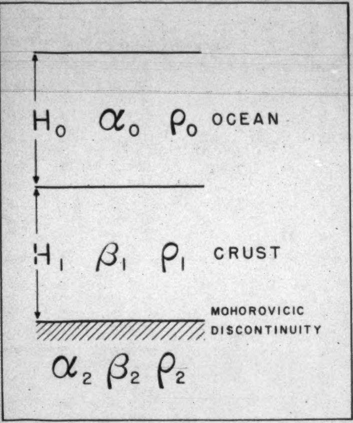


Fig. 3--Chart showing use of symbols

South Pacific Basin--In the investigations to be discussed in the following sections, an attempt at objectivity was made by including all the earthquakes which had appropriate paths in a given span of years long enough to give adequate coverage and which had good epicenters and origin times and readable records at the receiving station. The consistency of the results for each area testifies to the usefulness of surface waves for the investigation of crustal properties. The earthquake epicenters, origin times, magnitudes, and the source of their determination are summarized in Table 3. The constants of the instruments are shown in Table 4. The method of determining the period was to assign consecutive half numbers to the peaks and troughs of a given train of waves and to plot the arrival time of the peak or trough against its respective number, the periods being tangents to the resulting curve. The theoretical curves on each graph are labeled with the assumed thickness and crustal velocity.

Table 2--Calculated H values for two values of α_1 ($\alpha_0 = 1.52$ km/sec, $\alpha_2 = 8.10$ km/sec, $\rho_1 = 2.67$, $\rho_2 = 3.00$, $\sigma = 0.25$)

α_1	C/α_0	$H = H_0$[a]		$H = 2H_0$		$H = 5H_0$		$H = 10H_0$	
		kH_0	U/α_0	kH_0	U/α_0	kH_0	U/α_0	kH_0	U/α_0
km/sec									
5.5	2.80	0.070	2.76	0.043	2.76	0.019	2.76	0.010	2.77
5.5	2.77	0.135	2.71	0.083	2.71	0.039	2.71	0.020	2.72
5.5	2.75	0.175	2.68	0.109	2.68	0.051	2.69	0.027	2.68
5.5	2.73	0.231	2.63	0.148	2.64	0.070	2.65	0.037	2.64
5.5	2.70	0.290	2.55	0.194	2.58	0.094	2.60	0.050	2.59
5.5	2.60	0.449	2.23	0.352	2.35	0.187	2.39	0.101	2.40
5.5	2.50	0.540	1.76	0.464	1.97	0.265	2.12	0.144	2.12
5.5	2.40	0.603	1.30	0.544	1.59	0.329	1.87	0.180	1.90
5.5	2.30	0.656	0.99	0.607	1.34	0.388	1.61	0.217	1.72
6.9	2.80	0.101	2.77	0.071	2.78	0.039	2.78	0.022	2.78
6.9	2.77	0.214	2.71	0.167	2.72	0.104	2.72	0.065	2.72
6.9	2.75	0.263	2.67	0.217	2.68	0.144	2.68	0.092	2.68
6.9	2.73	0.334	2.60	0.292	2.63	0.200	2.63	0.121	2.63
6.9	2.70	0.398	2.48	0.366	2.54	0.256	2.56	0.152	2.55
6.9	2.60	0.521	1.97	0.504	1.95	0.381	2.20	0.236	2.27
6.9	2.50	0.583	1.34	0.566	1.43	0.463	1.87	0.307	2.14
6.9	2.40	0.631	1.11	0.617	1.17	0.538	1.68	0.414	2.07
6.9	2.30	0.682	0.97	0.670	1.02	0.614	1.62	0.562	1.99

[a] The figures for $H = H_0$ differ slightly from Jardetsky and Press.

Table 3--Data on earthquake epicenters, origins, and magnitudes

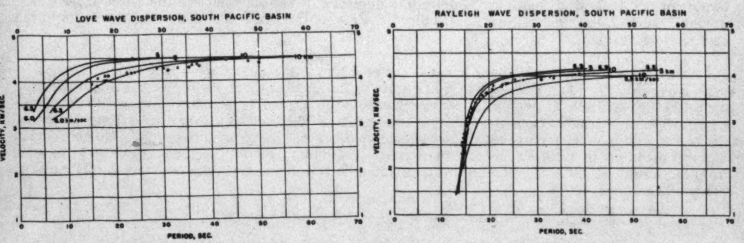
Location	Date	Original time GMT	Epicenter		Epicentral distance	Magnitude	Reference	Symbol	Figure
			Lat.	Long.					
		h m s	°	°	°				
South Pacific Basin (Easter Island to Christchurch)	Apr. 30, 1950	10 29 03	24 1/2 S	112 1/2 W	6.28	....	USC&GS 42-50	▼	4ab
	July 9, 1950	01 39 29	33 S	112 W	58.1	....	USC&GS 74.50	▲	4ab
	Sep. 22, 1950	07 52 07	25 S	114 W	61.4	6 1/2 - 6 3/4	USC&GS 111-50	■	4ab
	Feb. 19, 1951	22 11 54	25 S	117 W	59.2	6 1/2	USC&GS 18-51	●	4ab
Tasman Basin (SW New Zealand to Riverview)	Sep. 4, 1945	17 14 18	46 1/4 S	165 3/4 E	16.7	5 1/2 - 6	N. Z. and Riverview	♦	6ab
	Aug. 8, 1947	05 32 48	46 S	166 E	16.6	5 1/2 - 6	N. Z. and Riverview	▲	6ab
	Aug. 8, 1947	20 18 38	46 S	166 E	16.6	5 1/2 - 6	N. Z. and Riverview	▼	6ab
	Aug. 9, 1947	05 33 16	46 S	166 E	16.6	5 1/2 - 6	N. Z. and Riverview	■	6ab
	Feb. 6, 1950	22 53 30	48 S	164 E	17.2	6 - 6 1/4	N. Z. and Riverview	●	6ab
East Cape - Kermadec - Tonga Ridge (Samoa and Tonga to Christchurch)	Jan. 27, 1950	19 18 09	17 S	173 W	28.8	....	USC&GS 8-50	▼	7ab
	Nov. 24, 1950	13 03 43	15 S	173 W	31.1	6 1/4 - 6 1/2	USC&GS 140-50	♦	7ab
	Nov. 24, 1950	20 18 48	15 S	173 W	31.1	6 1/4 - 6 1/2	USC&GS 140-50	●	7ab
	Apr. 1, 1952	14 08 47	15 S	175 1/2 W	30.3	6 1/4	USC&GS 43-52	▲	7ab
	Sep. 16, 1953	01 48 42	15 S	174 1/2 W	30.6	6 1/4 - 6 1/2	USC&GS 124-53	■	7ab
	Mar. 3, 1952	07 12 39	21 1/2 S	174 1/2 W	24.5	6	USC&GS 28-52	△	7ab
	Aug. 12, 1953	16 53 42	22 S	175 W	23.9	6 - 6 1/2	USC&GS 104-53	▽	7ab
Lord Howe Rise (W New Zealand to Brisbane)	June 19, 1948	06 18 39	43 1/4 S	169 1/4 E	20.4	5 3/4	N.Z. Stations	▲	9
	June 19, 1948	07 05 36	43 1/4 S	169 1/4 E	20.4	5 3/4	N.Z. Stations	▼	9
Solomons to New Zealand (Solomons to Christchurch)	July 7, 1950	16 46 55	11 S	163 1/2 E	33.7	....	USC&GS 73-50	●	10
	Oct. 15, 1950	15 59 33	10 S	160 E	35.3	6 1/2	USC&GS 122-50	▲	10
	Nov. 8, 1950	02 18 09	9 1/2 S	159 1/2 E	35.9	7 1/4 - 7 1/2	USC&GS 136-50	▼	10
Fiji Basin (Fiji to Christchurch)	Dec. 22, 1940	12 31 44	14 S	178 E	29.9	6 1/2	Gutenberg and Richter	▼	11
	Oct. 21, 1943	23 08 13	15 S	177 1/2 E	28.8	7	Gutenberg and Richter	●	11
	Sep. 27, 1950	08 23 52	18 1/2 S	175 E	25.1	6 1/2	USC&GS 114-50	■	11
	Apr. 5, 1952	08 33 12	15 1/2 S	177 1/2 E	28.4	6 - 6 1/4	USC&GS 46-52	▲	11

The results for the South Pacific Basin are presented in Figure 4. For the Love waves the experimental points predict a crustal thickness slightly greater than 10 km for a mean crustal velocity between 6.0 and 6.5 km/sec. For the Rayleigh waves the experimental points predict a thickness of 5-10 km for a mean velocity. If the lower crustal velocity of 5.5 km/sec were chosen, the thickness would be 5 km; and if the higher velocity of 6.9 km/sec were chosen, the thickness would be somewhat greater than 10 km. These two graphs illustrate the kind of results that can be obtained. The crustal thicknesses are quoted to 5 km for an average crustal velocity of 6.2-6.3 km/sec, and to that order of magnitude the results are correct for any reasonable variation from this average velocity that might occur under particular structures.

It is interesting to compare these results with those obtained by OLIVER, EWING, and PRESS [in press] for the North Pacific. Figure 5 is a replot from their paper. The Love wave data are from earthquakes around the perimeter of the Pacific at various azimuths to Hawaii. The data from the southwest are from earthquakes in South America whose travel path is across the basin between

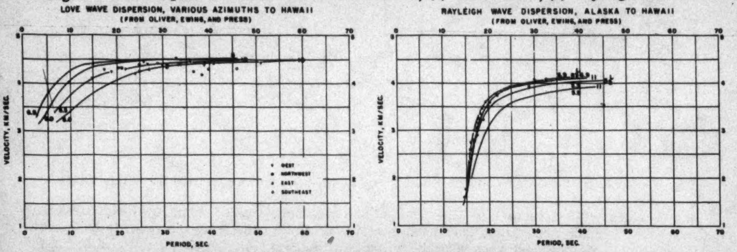
Table 4--Instrumental constants

Station	Instrument	Pendulum period	Galvanometer period	Magnification
		sec	sec	
Christchurch	Galitzin N-S	24	24	265
	Galitzin E-W	24	24	275
	Galitzin Z	13	13	465
Riverview	Galitzin N-S	12	12	540
	Galitzin E-W	12	12	530
	Galitzin Z	11	11	460
Brisbane	Milne-Shaw N-S	12	...	250
	Milne-Shaw E-W	12	...	250


LOVE WAVE DISPERSION, SOUTH PACIFIC BASIN

RAYLEIGH WAVE DISPERSION, SOUTH PACIFIC BASIN

Fig. 4--Wave dispersion in the South Pacific Basin; (a) Love waves, (b) Rayleigh waves


LOVE WAVE DISPERSION, VARIOUS AZIMUTHS TO HAWAII (FROM OLIVER, EWING, AND PRESS)

RAYLEIGH WAVE DISPERSION, ALASKA TO HAWAII (FROM OLIVER, EWING, AND PRESS)

Fig. 5--Wave dispersion, various azimuths to Hawaii (after Oliver, Ewing, and Press); (a) Love waves, (b) Rayleigh waves

South America and the Easter Island Rise and is interpreted by them as indicating a thicker crust under this basin. The data from the other azimuths are consistently higher than that for the South Pacific indicating a thickness somewhat greater than 5 km. The Rayleigh wave data show the same pattern giving a crustal thickness of 5 km. The crust is slightly thicker under the South Pacific Basin than under the North Pacific Basin.

Tasman Basin--The results for the Tasman Basin are presented in Figure 6. The Love waves give a thickness of 5-10 km. The experimental points do not fit any of the four theoretical curves very well; a more satisfactory agreement could be obtained by taking an 8-km crust in which the velocity varied from 6.0 km/sec near the top to 6.5 km/sec near the bottom. The Rayleigh waves predict a thickness of slightly greater than 10 km for a mean crustal velocity.

An important conclusion from these results is that the crustal structure under the Tasman Basin is oceanic and not continental. The hypothesis that the area from Australia to New Zealand

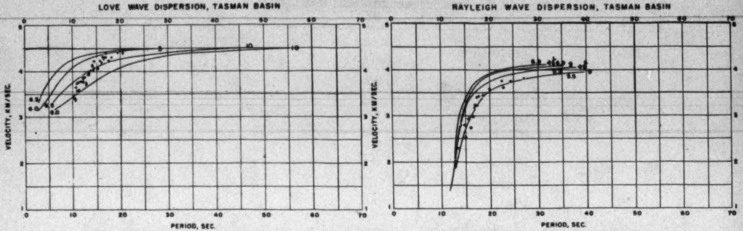


Fig. 6--Wave dispersion, Tasman Basin; (a) Love waves, (b) Rayleigh waves

is part of the Australian continent is definitely disproved. The thickness of the crust under the Tasman Basin to the west of New Zealand is the same as that under the South Pacific Basin to the east of New Zealand.

East Cape - Kermadec - Tonga Ridge--The results for the East Cape - Kermadec - Tonga Ridge bordering the South Pacific Basin are quite different than those for either the South Pacific, North Pacific, or Tasman Basins. They are presented in Figure 7. For the Love waves the thickness is 25 km for a mean crustal velocity between 6.0 and 6.5 km/sec. For the Rayleigh waves part of the path is across an ocean of average depth 1 1/2 km and part across land. No correction has been made for this difference, and the results are to be taken only as a check on the Love waves. From the lower velocity curves the thickness would be 20 km and from the higher velocity curves greater than 30 km.

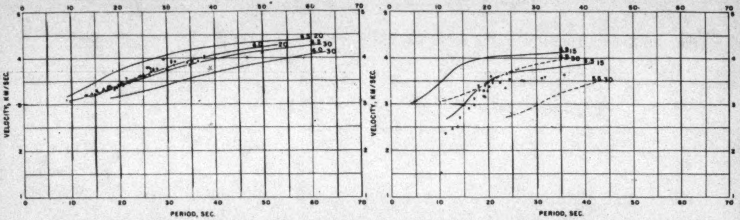


Fig. 7--Wave dispersion, Tonga - Kermadec Ridge; (a) Love waves, (b) Rayleigh waves

New Zealand--The structure of New Zealand has been investigated from local earthquake studies. HAYES [1935] recognized that crustal pulses could be read from the records of the New Zealand stations. He obtained lines with the velocities: P_n, 8.3; P_q, 7.3; P^*, 6.5; P_g, 5.4; S_n, 4.5; S^*, 3.8; and S_g, 3.4 km/sec. BULLEN [1936] determined a three-layered crust with P and S velocities respectively of 4.7 and 2.8 km/sec, 5.5 and 3.3 km/sec, 6.3 and 3.7 km/sec, and 8.10 and 4.37 km/sec for the successive layers and the subcrust; a formal solution for the thicknesses gave a total depth to the Mohorovicic discontinuity of 18 km. Later from additional data BULLEN [1939] revised this to a structure of an upper layer of 5-10 km with a P velocity of 5.0 km/sec, a second questionable layer of 4 km with a P velocity of 5.5 km/sec, and a third layer of 10-20 km with a P velocity of 6.3 km/sec. For the total depth to the Mohorovicic discontinuity he preferred an upper value of 30 km. EIBY [1949] has verified the identification of the phases traveling through the sedimentary basement, 'intermediate' layer, and subcrust and has pointed out from routine local seismogram interpretation that there is a strong probability of regional differences in the crustal properties under New Zealand.

In 1947, E. I. Robertson and the staff of the New Zealand Geophysics Division carried out a crustal refraction profile on a line northeast from Wellington. A series of strings of depth charges were fired in Wellington harbor and recorded at portable stations on the greywacke basement out to a distance of 175 km. All the records were taken with high speed recording equipment, from two to 12 inches per second, and with accurate shot instants. The experiment and the results will be given in detail in a memoir from the New Zealand Geophysics Division. Various people have examined the data; the following is the author's interpretation. The first arrivals from the records determine a straight line with a velocity of 5.54 km/sec out to a distance of 28 km (Fig. 8). This refraction can continue to be read as a strong second arrival for another 20 km. The layer above it in Wellington harbor was not determined; but it is thin, not greater than 0.3 km, with a velocity less than 2.0 km/sec. The second refractor with a velocity of 6.04 km/sec first appears as a second arrival at 15 km. At the longer ranges it has a velocity of 6.40 km/sec. The nature of the transition from a velocity of 6.04 km/sec to 6.40 km/sec can be seen from the second graph of Figure 8, which is a plot of the observed travel time minus the distance divided by a velocity of 6 km/sec, giving an expanded time scale. The change from 6.04 to 6.40 km/sec is fairly abrupt occurring at a distance of 90 km, more indicative of a discontinuity than a gradual change in velocity throughout the layer. The definition of P_n is not as satisfactory as one might desire. Two clear first arrivals out in front of the 6.04-6.40 km/sec lines from 85 to 95 km and three strong second arrivals from 70 to 80 km determine a line with a velocity of 8.10 km/sec. The three records from 95 to 120 km are not of sufficiently good quality to allow an early arrival to be read, and on the records at greater distance no early arrival can be detected. Support for the P_n line comes from a strong reflection, the most prominent on the records, which is observed at all stations from 15 to 40 km. The depth of this reflector agrees with that obtained for the Mohorovicic discontinuity from the P_n refraction line. The resulting thicknesses are 3 km of 5.54 km/sec, 7 km of 6.04 km/sec, and 8 km of 6.40 km/sec giving a total depth to the Mohorovicic discontinuity of 19 km.

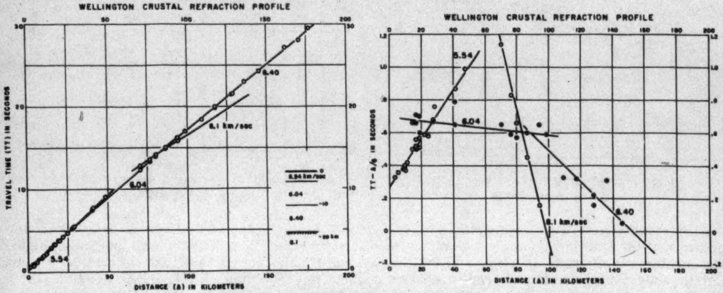


Fig. 8--Wellington crustal refraction profile; (a) using observed travel times, (b) using travel times minus Δ/6

The upper layer of 3 km of 5.54 km/sec is the greywacke basement on which the recording stations were located. It is of undifferentiated Jurassic - Triassic - Permian age. From its seismic velocity and its stratigraphic position the 7 km of 6.04 km/sec is interpreted as metamorphosed greywacke and probably older metamorphosed rock. The total of 10 km for the present thickness of the original geosynclinal sediments is of the order expected by BRODIE [1953] from a stratigraphic section near Wellington and by WELLMAN, GRINDLEY, and MUNDEN [1952] from the Alpine schists and Upper Triassic of the South Island. Indeed from a direct extrapolation of the surface geology to depth over parts of the South Island still greater thicknesses are expected by these authors. From its seismic velocity and its position above the Mohorovicic discontinuity the 8 km of 6.40 km/sec is interpreted as the 'intermediate' layer of seismology.

This crustal section argues for an origin of New Zealand from an original oceanic crust, not a reworked continental mass. The geosynclinal sediments deposited in earlier deep sea trenches have been uplifted and reach a thickness of 10 km under this profile. They are underlain by a crust of 'intermediate' layer velocity typical of that found under the undisturbed ocean basin areas. New Zealand has been part of the presently active orogenic belt of the outer island arcs, the previous belt of the inner island arcs, and possibly a still earlier belt along the Lord Howe Rise. Whereas the orogenic belts to the northwest have progressed outward with geologic time, the active region around New Zealand has remained central with the sediments from the older orogenic belts being eroded and deposited in the new.

Lord Howe Rise--The results for the Rayleigh wave dispersion along the Lord Howe Rise are presented in Figure 9. It was not possible to read a train of Love waves from the records for these two earthquakes. A curve for a 15 km crust with a mean velocity between 5.5 and 6.9 km/sec would be somewhat too thin to fit the experimental data. A thickness of 20 km is chosen. The paths for these two earthquakes to Brisbane are along the flank of the Lord Howe Rise; the crust may be thicker along the central portion of the Rise.

Solomons to New Zealand--The results for earthquake paths from the Solomons to Christchurch are presented in Figure 10. With the variable depth of water over the path only the Love waves were considered. The thickness for a mean crustal velocity between 6.0 and 6.5 km/sec would be 15-20 km. This value is a composite thickness over the entire path. The actual crustal thickness under the northern, basin area is probably thinner than this value and that under the southern, ridge and rise area thicker.

DE JERSEY [1946] examined Rayleigh waves from the Solomons, Samoa, and the Kermadecs to Brisbane. Neglecting the effect of the ocean on the Rayleigh wave dispersion curves, he obtained too great a thickness, which varied with the period of the surface waves. Including the ocean in the Rayleigh wave dispersion curves his results all lie on the same line and are in agreement with results given above. He also examined the ratio PP/P of the reflected to direct P phases and concluded that the Southwest Pacific was of continental structure. A. A. Thomson of the Seismological Observatory, Wellington, in a paper at the Geophysical Conference of 1951, has carried out a similar investigation and obtained results showing oceanic (4), intermediate (2), and continental (1) PP/P ratios for the Southwest Pacific. He concluded that the method was unsuitable for differentiating between crustal structures in this area.

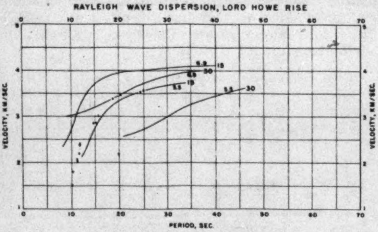


Fig. 9--Rayleigh wave dispersion, Lord Howe Rise

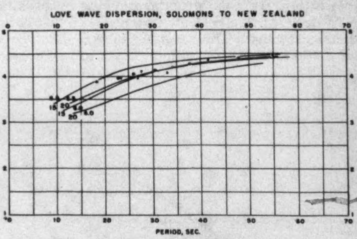


Fig. 10--Love wave dispersion, Solomons to New Zealand

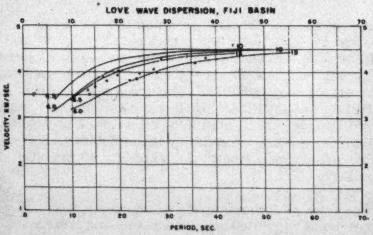


Fig. 11--Love wave dispersion, Fiji Basin

Fiji Basin--The results for the Fiji Basin are presented in Figure 11. Again only the Love waves were considered. The plotted data have been corrected for the portion of the path across New Zealand from the offshore slope and for the Fiji area on a 25-km crust to isolate the effect due to the Fiji Basin alone. From the graph a thickness of 15-20 km is predicted for a mean crustal velocity. This is greater than the thickness of the deep basins exterior to the orogenic belts.

Conclusions--The values for the crustal thicknesses are summarized in Table 1. From the surface waves the crustal thickness under the South Pacific Basin is slightly greater than that under the North Pacific Basin. The thickness of the crust under the Tasman Basin is the same as that under the South Pacific Basin. It is an oceanic and not a continental type crust. The interior region of the orogenic belts including New Zealand have been built up with succeeding geologic time on an oceanic crust. They are not part of an extensive continent. The thicknesses are not of continental proportions nor does the structure indicate a continental origin. The structure is that of successive orogenic belts built out over an oceanic crust.

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MEASUREMENT AND STATISTICAL EVALUATION OF LOW-LEVEL RADIOACTIVITY IN ROCKS

H. A. Slack and W. C. Krumbein

Abstract--Methodology is discussed for detecting and evaluating low levels of radioactivity of rocks, as measured by alpha particle emission. Applications are made to the radioactivity of samples of black shale, which range in activity from 0.94 to 8.96 alpha particles per minute per 1.5-inch diameter circular surface of powdered material. A two factor analysis of variance design with multiple cell entries is used to test for homogeneity of means within a small sampling grid in black shale. Plans to extend this method to a study of regional radioactive variation within a stratigraphic unit are also discussed.

Introduction--Most rocks show a low level of radioactivity as measured by alpha particle emission. Emphasis seems to have been largely on the study of higher levels of radioactivity, and it is perhaps desirable to investigate activity nearer the threshold level. The present study is concerned with the measurement and evaluation of low-level radioactivity of rocks with a view later to study the regional variation within certain selected stratigraphic units. Some of these stratigraphic units, in particular black shales associated with Pennsylvanian cyclothems, extend over large areas and are remarkably uniform in thickness and general lithologic character. It would therefore be of interest to see whether the regional pattern of radioactivity shows similar uniformity due to environmental control.

This paper presents results thus far obtained, it describes certain applications of statistical theory to the data, and it outlines plans for future work.

Instrumentation and counting procedure--The radioactivity of powdered rock samples was obtained by using a Radiation Counter Laboratory alpha scintillometer containing a 1.5-inch diameter activated zinc sulphide phosphor. The sample to be measured was crushed to less than 1/8 mm. and placed in a source dish thick enough to be considered infinitely thick for alpha ray emission. Counts were recorded on a conventional type scaling device.

Statistical evaluation of counting observations--Statistical tests verify the known fact that counting observations are samples drawn from a population distributed in accordance with the Poisson law. Figure 1 shows the distribution of counts recorded over 400 one minute intervals for two samples of powdered black shale as well as the distribution of background counts for 464 one minute intervals. In all cases a χ^2 test for goodness of fit to a Poisson distribution was acceptable (SNEDECOR, 1946, p. 441).

Inspection of successive one minute counts suggests that they are randomly distributed about the mean value. Control chart methods [SHEWHART, 1931] as applied to Geiger-Mueller counting instruments by SCHLECHT [1946] were not used to test whether disturbing effects of a cyclical nature were present in the instrument during the several weeks' time in which the 400 or so one minute counts were recorded. However, the acceptable fit to the Poisson distribution is tentatively taken as evidence that there were no intermittent instrumental effects such as those described by SELIGER [1950].

An approximate confidence interval at the 0.95 confidence level can be constructed for the counting rate by the interval $(x/t) \pm (1.96 \sqrt{x})/t$ [BIRNBAUM, 1954], where x is the total number of observed counts in time t. In the present study x was selected to be 100, and inasmuch as all samples of black shale dealt with thus far in the study had an activity at least ten times as high as background activity, the confidence interval is equal to approximately 20 pct x/t, the best estimate of the counting rate. The confidence interval at the 0.99 confidence level, and with an $x = 100$, would be equal approximately to 25 pct of the best estimate of the counting rate. It is interesting to note that a total count of 400 would be required to reduce this confidence interval to ten per cent at the 0.95 level.

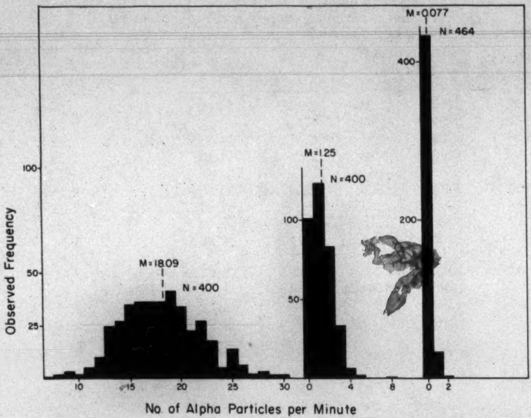

Fig. 1--Histograms showing distribution of counts for two samples of powdered black shale and (right diagram) for the instrumental background; note change in vertical scales

Statistical evaluation of variability within a rock unit--As a first approach to the study of regional variation in radioactivity, a Pennsylvanian black shale unit 20 inches thick was sampled in a strip mine. The black shale overlies Coal no. 6, in Saline County, Ill., and the freshness of the exposure precluded significant weathering effects.

The design of the sampling grid is shown in Fig. 2. To avoid bias the position of the first section was randomized on the mine wall and the other three sections were then laid off at ten-foot intervals. The top and the bottom of the shale had been thought to be higher in radioactivity than the central portion, and samples were taken to segregate the top and bottom two inches from the central section, which was divided into two equal sampling zones. Four samples were selected at random from each of the zones on the four traverses, yielding 64 samples in all. The radioactivity expressed as alpha particles per minute per 1.5-inch diameter circular surface of powdered material was measured for each sample on the basis of 100 total counts. The results obtained are shown on the left side of Table 1, which shows four values in each sampling 'cell'.

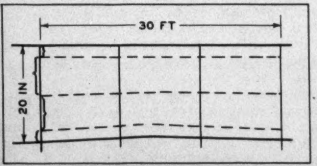

Fig. 2--Sampling grid for evaluating variability of radioactivity within a small section of black shale unit

Application of the analysis of variance assumes homogeneity of variances [EISENHART, 1947]. Cochran's test for homogeneity of variance [DIXON and MASSEY, 1951, p. 147] within the 16 individual cells shows inhomogeneity of the original data at the five per cent level and homogeneity at the one per cent level. In view of this marginal value the square root transformation [BARTLETT, 1947] was applied to the original data to stabilize the variance. The transformed values are shown on the right in Table 1. Cochran's test applied to the transformed data showed variance homogeneity at the five per cent level. The analysis of variance was accordingly conducted with the transformed values.

The analysis of variance of transformed data in Table 1 is shown in Table 2. The design is a two factor basic form with multiple cell entries [DIXON and MASSEY, 1951, p. 134]. A 'null' hypothesis was set up to the effect that there is no significant difference among the column means or the

Table 1--Variation of radioactivity within sampling grid; data expressed as alpha particles per min. per 1.5-inch diameter circular surface of powdered material

	Original data along bed					Transformed data (square-root transformation) along bed			
across bed	1.15	1.10	2.24	2.87	across bed	1.07	1.05	1.50	1.69
	1.38	1.51	1.63	5.79		1.17	1.23	1.28	2.41
	1.75	1.21	1.26	5.33		1.32	1.10	1.12	2.31
	2.60	1.57	3.88	1.09		1.61	1.25	1.97	1.04
	0.94	1.22	3.00	2.44		0.97	1.10	1.73	1.56
	3.48	4.46	1.06	1.57		1.87	2.11	1.03	1.25
	4.37	1.46	1.11	5.73		2.09	1.21	1.05	2.39
	8.96	1.30	1.29	2.14		2.99	1.14	1.14	1.46
	7.01	3.82	4.30	3.38		2.65	1.95	2.07	1.84
	1.74	1.64	3.70	3.57		1.32	1.28	1.92	1.89
	7.33	4.75	2.31	5.49		2.71	2.18	1.52	2.34
	2.42	1.27	2.25	2.82		1.56	1.13	1.50	1.68
	2.02	3.48	2.88	1.22		1.42	1.87	1.70	1.10
	2.18	1.11	1.58	1.44		1.48	1.05	1.26	1.20
	2.34	2.51	4.26	2.15		1.53	1.58	2.06	1.47
	2.52	5.00	1.24	1.07		1.59	2.24	1.11	1.03

Table 2--Analysis of variance for data of Table 1

Source	Sum of squares	Degrees of freedom	Mean square	F[a]
Between columns (along bed)	0.6989	3	0.2330	1.06 NS
Between rows (across bed)	1.5802	3	0.5267	2.39 NS
Interaction (column X row)	2.6335	9	0.2926	1.41 NS
Residual	9.9288	48	0.2069	. . .
Total	14.8414	63		

Combined error = 12.5623/57 = 0.2203

[a] NS = not significant.

row means at the five per cent significance level, and that no significant interaction is present between columns and rows at the same significance level.

Inasmuch as the design is used to test the relationship among fixed means, the model is in Class I as described by EISENHART [1947]. Dixon and Massey show the computations, which separate the total sum of squares into four parts, the first assigned to a column effect (along-bed variance), the second assigned to a row effect (across-bed variance), the third to a 'row X column' interaction, and the last to a residual 'within cells' variability. The sums of squares are divided by their degrees of freedom to obtain the mean squares shown in Table 2.

The standard procedure is to test the interaction mean square against the residual. If it is non-significant, as in the present case, the interaction sum of squares is pooled with the residual to obtain a combined error term as shown. The column and row effects are then tested against this pooled error. The tests are conducted by setting up F ratios with the combined error as denominator, and checking the values in appropriate tables [DIXON and MASSEY, 1951, p. 310]. Neither of the main effects is significant at the five per cent significance level, and as a result the null hypothesis is not rejected.

The lack of statistically significant column or row effects in the sampling grid suggests that all of the samples could have been drawn from a single homogeneous population. An unbiased estimate of the population mean is the arithmetic mean of the 64 samples, or 2.74 alpha particles per minute per 1.5-inch diameter circular surface of powdered material. This absence of significant variation in the sampling grid is due in part to the large 'within cell' variability. Confidence limits computed for the individual values within any cell could be reduced by counting over longer periods of time but this will not necessarily reduce the cell variance. For this reason the expenditure of additional time in the measuring process was not considered necessary.

Proposed study of regional variation in radioactivity--The preceding estimate of the population mean from the sampling grid may be taken as representative of the part of the strip mine sampled. In designing a study to evaluate regional variation in the radioactivity of Pennsylvanian black shales it would be desirable to avoid the necessity of analyzing thousands of samples represented by such detailed sampling grids in numerous strip mines. The present experiment indicates that there is a fairly large 'within variability' among closely spaced samples, so that even larger effects must be found regionally to establish radioactivity gradients in the total population.

The absence of interactions in this experiment, if general, also would eliminate the need for sample replication within the grid cells.

In order to evaluate the variance contributions at different levels of sampling, it is proposed to use a hierarchial method of sampling, essentially following POTTER and SIEVER [in press] in setting up 'supertownships' as major sampling units, and randomizing townships within them, followed by randomization of strip mines within townships, and randomization of samples within mines. This hierarchial sampling design will be supplemented by sampling grid studies within one or more supertownships to evaluate in more detail the variances within and between mines or within and between locations in the same mine.

Although individual samples have their radioactive counts distributed according to the Poisson law, the distribution of the mean values represents a continuous variable. It is recognized that the 64 closely spaced samples are insufficient to establish any generalizations, but it is instructive to examine their distribution function, as shown in Figure 3. The skewness of the histogram suggests a two parameter Gamma distribution [MOOD, 1950, p. 112], and the smooth curve through the data is such a frequency curve, based on the observed mean of 2.74 and on a variance computed from the total sum of squares in Table 2 divided by 63 degrees of freedom.

If the regional population is similar to the local population suggested by Figure 3, it may be anticipated that among the additional samples collected the majority will cluster about a relatively low modal value, with a finite number of samples showing markedly higher radioactivity. This tentative prediction will be checked more fully in the regional study.

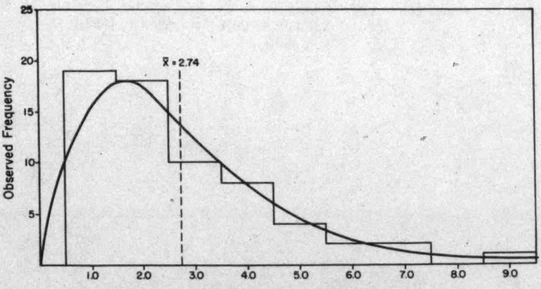

Fig. 3--Distribution of mean values of radioactivity within sampling grid of Figure 2; the smooth curve is a fitted two parameter Gamma distribution; N = 64

Concluding remarks--The present paper is a progress report in the application of statistical methods to the measurement of low level radioactivity of certain black shales. It is believed that the results show the possibility of estimating the radioactivity within confidence limits selected by the investigator, although narrow limits may involve prohibitive counting times for each sample. The use of analysis of variance in designing a sample plan also showed that although the radioactivity varies markedly among closely spaced samples, this variation is such that it may represent a homogeneous population in any one sampling area. Hence, a lesser number of samples from the grid could be used to estimate the mean radioactivity at the sampling point. This is important in designing a regional study, inasmuch as it eliminates the necessity of having almost innumerable closely-spaced samples. Moreover, by designing the regional plan on a hierarchial basis, the total degrees of freedom in the experiment may be distributed over several levels to permit estimation of the variance introduced at any level of sampling, and to provide adequate degrees of freedom for estimating parameters of the total regional population.

Acknowledgments--The writers are particularly indebted to J. A. Simon, Head of the Coal Division of the Illinois State Geological Survey for furnishing samples used in this study. His continued interest in the project and the cooperation of Paul E. Potter of his staff in designing sampling plans are greatly appreciated.

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WERE THE CAROLINA BAYS ORIENTED BY GYROSCOPIC ACTION?

William Schriever

Abstract--All the effects of the spin of the Earth on the water in a circular eddy two miles in diameter and 100 ft deep, having a water velocity of four miles per hour near the shore, were investigated. The deflection-to-the-right, together with the centrifugal reaction out from the center of the eddy, cause the level of the water everywhere near the shore to be approximately six inches higher than it is at the center of the eddy. The change in the centrifugal reaction out from the Earth, due to the horizontal velocity of the water relative to the Earth, causes the water (in a clockwise eddy) to be less than a sixteenth of an inch higher near the north shore than near the south shore. It appears that these effects could cause neither ellipticity, nor influence the orientation of an eddy, for example, a Carolina Bay. Contrary to the assumption by COOKE [1954], an eddy does not exhibit gyroscopic action.

Introduction--COOKE [1954] presents an explanation for the ellipticity and the orientation of the Carolina Bays. This explanation is based on an assumed gyroscopic property of a rotating body of water. The following quotations from pages 196 and 197 of Cooke's paper have been numbered for later reference. Some of these statements will bear reconsideration.

(1) 'However, it may be assumed that a drop of liquid moving in a curved path obeys the same laws of motion as a solid particle moving in a curved path,' (2) 'and that a rotating body of liquid will behave in the same manner as a rotating solid body,' (3) 'except insofar as its action will be modified by its lack of rigidity.' (4) 'Because of its inherent inertia every particle of matter resists change in the direction of its motion. This resistance is manifested in the gyroscope, an adaptation of the flywheel. A spinning flywheel tends to keep the direction of its plane of rotation fixed in space.' (5) 'An eddy presumably responds in the same manner, though gravity holds its surface nearly horizontal.'

With item (1) we are pleased to agree. Item (2) must be incorrect as far as the gyroscopic effect is concerned. Gyroscopic action is the property of a rigid body only. Thus if item (3) included an appropriate explanation, it would nullify item (2) as written.

With item (4) we are also pleased to agree. Again item (5) is not in accord with known facts since an eddy of water is not a rigid body. This lack of gyroscopic action of a rotating body of liquid was pointed out by SCHRIEVER [1951] but no detailed discussion of the problem was given.

The effects of the rotation of the Earth on the water in a circular 'bay', when that water is in steady rotation as in an eddy, will now be discussed. All these effects are in accord with item (1) quoted above. If an eddy exhibits gyroscopic action, the consideration of all the phenomena associated with the separate particles will reveal it. Any other effects of the spinning Earth on an eddy will also be revealed. An exact solution of the problem for both small and large velocities of the water in an eddy would be extremely complicated and, fortunately, is quite unnecessary. The solution given herein is a good approximation for low water velocities, say up to ten miles per hour. Therefore, valid conclusions may be drawn from the results.

Deflection-to-the-right--First let us consider deflection-to-the-right. A particle of water which is moving over the surface of the spinning Earth, behaves as if it were acted on by a force which causes it to be deflected-to-the-right in the northern hemisphere. The magnitude of this force is given by HUMPHREYS [1940 p. 116] in the well-known equation

$$F = 2mv\,\Omega\,\sin\phi \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where m is the mass of the particle, v is its velocity over the surface of the Earth, Ω is the angular velocity of the Earth, and ϕ is the angle of latitude of the particle. It is important to note that this force is the same for all geographic directions of motion of the particle (it is the horizontal component of the Coriolis 'force').

Let us consider a particle of water near the shore of a circular bay two miles in diameter and located at 30° north latitude. If the water is rotating clockwise as viewed from above, such that our particle near the shore has a velocity of four miles per hour, this particle will be acted on by a force toward the center of the bay; its magnitude is given by (1). Since the particle is moving in a circle it has a centrifugal reaction outward given by mv^2/r where r is the radius of the circle of rotation of the particle. The deflecting force is very small, and it is of interest to compare it to the centrifugal reaction. The ratio is

$$\text{Deflecting force} / \text{Centrifugal reaction} = 2\Omega \sin \phi / w = 2r\Omega \sin \phi / v \simeq \pi/48 \simeq 0.07 \quad ..(2)$$

where w is the angular velocity of the eddy, since r = one mile, v = four miles per hour, $\Omega \simeq \pi/12$ radian/hr, and sin 30° = 1/2.

Thus the deflection-to-the-right will decrease the centrifugal effect by approximately seven per cent at every point in this bay. If the rotation of the water were counterclockwise, the centrifugal effect would be increased by the same fraction at every point.

Since both the centrifugal effect and the deflection-to-the-right effect are independent of the geographic direction of motion of the particle of water, any erosion of the shore due to the motion of the water would be the same along the entire circumference of the bay. There would be no tendency to erode more on the NW and SE sides of the circular bay so as to make it into a Carolina-type elliptical bay having its long axis NW-SE.

Change of weight--Next let us consider the change in the force of gravity which acts on the particle in motion. A particle of water moving along the surface of the Earth is also subject to a centrifugal reaction out from the Earth (this is the vertical component of the Coriolis force). If the particle is moving due east, its velocity relative to the Earth will be added directly to that of the surface of the Earth (caused by the spin of the Earth). If the particle is moving due west, its velocity will be subtracted from that caused by the spin of the Earth. To solve this problem we must have a clear picture of the nature of the strength of gravity at a point on the spinning Earth.

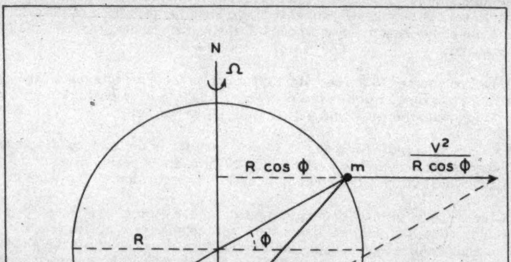

Fig. 1--NS is the axis of the Earth, Ω its angular velocity of spin, R its radius, ϕ is the angle of latitude of the particle of mass m, V is the instantaneous absolute velocity of m (into the paper) due to the spin of the Earth, g_0 is the gravitational attraction of the Earth per unit mass of m, and g is the strength of gravity at the point where m is located

In Figure 1 the gravitational attraction of the Earth is in the direction g_o and equal to mg_o. Because the Earth is spinning, m has a centrifugal reaction $mV^2/R \cos \phi$ directly away from the axis of spin, NS. The resulant force of the Earth on m is thus in the direction g and equal to mg. From Figure 1 it is evident that

$$g^2 = g_o^2 + V^4/R^2 \cos^2 \phi - 2g_oV^2/R \ldots\ldots\ldots\ldots\ldots \quad (3)$$

If the particle m were moving due east (directly into the paper in the figure) with a velocity v_e relative to the Earth, then the force per unit mass on m would be given by

$$g_e^2 = g_o^2 + (V + v_e)^4/R^2 \cos^2 \phi - 2g_o (V + v_e)^2/R \ldots\ldots\ldots \quad (4)$$

At latitude $\phi = 30°$, V is 1320 ft/sec. Thus if the particle of water (m) in a bay were moving east at four miles per hour (5.86 ft/sec), the difference between the second terms on the right-hand sides of (3) and (4) would be very small compared to the difference between the third terms and may therefore be neglected.

Subtracting (4) from (3), we have

$$g^2 - g_e^2 = 2g_o [(V + v_e)^2 - V^2]/R \ldots\ldots\ldots\ldots\ldots \quad (5)$$

The left-hand side may be written $(g - g_e)\, 2g_o$ since g, g_e, and g_o differ only slightly from each other. Then, since $V = \Omega R \cos \phi$ and since $2Vv_e$ is very large in comparison to v_e^2, we may reduce (5) to

$$g - g_e = 2\, \Omega\, v_e \cos \phi \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

Thus $(g - g_e)$ is the decrease in the strength of gravity which acts on a particle of water at latitude ϕ when it is moving due east horizontally at velocity v_e with respect to the Earth.

We may calculate this. $\Omega = 2\pi/86164 = 7.29 \times 10^{-5}$ rad/sec. Water moving four miles per hour makes $v_e = 5.86$ ft/sec. At latitude 30°, $\cos \phi = 0.866$. Thus

$$g - g_e = 7.4 \times 10^{-4} \text{ ft/sec}^2 \ldots\ldots\ldots\ldots\ldots \quad (7)$$

Since g is approximately 32 ft/sec^2

$$\Delta g/g = 2.3 \times 10^{-5} \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

Thus the strength of gravity, acting on a particle of water moving east at four miles per hour, decreases by only 2.3 parts in 100,000.

If the water were moving due west, v_e in (4) would be negative and the right-hand member of (6) would give the increase in the strength of gravity acting on the particle of water.

If the particle of water were moving with a velocity v in another direction, say north of east, then the absolute velocity V_o of the particle would be the vector sum of V and v as shown in Figure 2.

From Figure 2 it is evident that

$$V_o^2 = (V + v_e)^2 + v_n^2 \ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

Thus the change in the strength of gravity acting on the particle will be a decrease in gravity given by (6) plus a further decrease given by v_n^2/R. If the particle were moving due north (or due south), the only change in gravity would be v_n^2/R (or v_s^2/R). If v_n (or v_s) is four miles per hour

$$v_n^2/R = 1.63 \times 10^{-6} \text{ ft/sec}^2 \ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

And the fractional change in the strength of gravity acting on the particle would be 5.1×10^{-8} or only five parts in a hundred million. Thus the due north (or due south) component of the velocity of the particle of water causes a negligible change in the strength of gravity compared to that caused by the due east or the due west component of the velocity. Since a particle moving west gets heavier and when moving north (or south) gets lighter, it is possible to move west of north

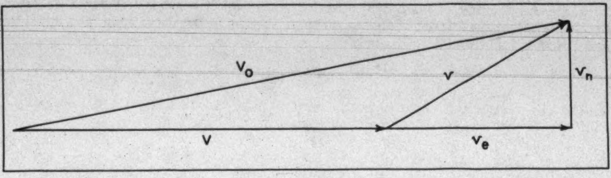

Fig. 2--The velocity of the particle of water with respect to the Earth is v; v_e is the east component of v and v_n is the north component of v; V is the absolute velocity of a point on the Earth at latitude ϕ; V_o is the absolute velocity of the particle of water

(or west of south) at such an angle that the two effects balance each other. A little calculation shows that, at a velocity of four miles per hour, this angle is only one eighth of a degree west of north (or west of south). This demonstrates the relatively very small effect due to v_n^2/R.

N-S difference in water level--We may now determine the difference in the level of the water between the north and the south sides of the two-mile-diameter bay located at 30° north latitude, and in which the water near the shore is moving steadily at four miles per hour in a clockwise direction.

First let us consider the deflection-to-the-right and the horizontal centrifugal effects. For a clockwise rotation of the water, these are oppositely directed but each is of the same magnitude all around the bay. Since the centrifugal effect is the larger, the results of these two effects will merely cause the water to be slightly concave (approximately six inches higher near the shore than in the center). Thus they will not cause any difference in level between two points near the shore and diametrically across from each other. Also the change in level between the center and the shore will be independent of the depth of the water in the bay.

Second, the north and south motions of the water, near the west and east shores respectively, will both cause the same changes in gravity (acting on the water) at the two shores, and therefore no difference in the water levels between the east and west sides of the eddy.

Third, the east motion of the water near the north shore will cause a decrease in the gravity acting on it of 7.4×10^{-4} ft/sec (see (7)). The west motion of the water near the south shore will cause an increase in gravity of 7.4×10^{-4} ft/sec^2. For easy visualization let us assume the bay to have a flat level bottom and that the water in the center is 100 ft deep. After the water in the bay has rotated until it has achieved dynamic equilibrium, the pressure at the bottom near the north shore must be approximately equal to that at the bottom near the south shore. Such approximate equilibrium pressures will be maintained by gravity because the difference in the levels is so very small and because the time required for one revolution is so great (nearly 1.6 hours). Thus $h_n g_n d = h_s g_s d$, where h is the depth of the water, d its density, and g is the effective strength of gravity. Since the strength of the gravity acting on a particle near the north shore is less than normal, the water there must be deeper, and we may write $h_n = h_s + \Delta h$, where Δh represents the difference in levels between the north and south shores. Also we may write $g_s = g_n + \Delta g$, where Δg is the gravity difference between points near the south and north shores. Substituting these two in the pressure equation above we have

$$\Delta h = h_s \, \Delta g/g_n \quad \ldots\ldots\ldots\ldots \quad (11)$$

For calculating Δh we may take $h_s = 100$ ft, and $\Delta g/g_n$ will be twice that given by equation (8) or 4.6×10^{-5}. Thus

$$\Delta h = 0.0046 \text{ ft or } 0.055 \text{ inch} \quad \ldots\ldots\ldots\ldots \quad (12)$$

Since only the east and west components of the velocity of the water cause a change in water level, the water will be highest near the north shore and lowest near the south shore, but even this difference will be less than a sixteenth of an inch. If the motion were counterclockwise, the water near the south shore would be higher than that near the north shore by the same amount. If the water were only 50 ft (instead of 100 ft) deep, the difference in levels would be only half as great.

Since the deepest water near the N shore gets shallower as it moves around the bay to the S shore, and the shallowest water near the S shore gets deeper as it moves around the bay to the N shore, there must be a movement of the water down along the east half of the bay, W well below the surface, and up along the W half of the bay. However, since the water near the N shore is less than 1/16 inch higher than that at the S shore, and since it takes 0.8 hour to complete the half revolution, the necessary circulation will be relatively very slow. This circulation also tends to reduce the difference in water level to a value even smaller than that given by (12).

Discussion of results--We have now considered the effects of all the 'forces' which act on the water in a circular bay when this water is rotating as in an eddy. All of the effects except the third act on the water in an exactly symmetrical manner. The third effect causes a difference in water level between the north and south shores of a bay filled with water in rotation. But this difference is so very small that it appears impossible that it could cause asymmetrical erosion of the shores.

A rigid body is acted on quite differently. If the spinning water in the bay were a spinning rigid cylinder, there would be no deflection-to-the-right of the cylinder as a whole since the force on any one particle of the cylinder would be balanced by an exactly equal and opposite force on a particle similarly situated diametrically across the cylinder. However, such a cylinder would exhibit a gyroscopic effect and would require a torque to hold it in its fixed orientation with respect to the Earth.

If the 'forces' due to the rotation of the Earth on water in motion caused geologically important erosional effects, then all rivers in the northern hemisphere should exhibit more erosion on their right banks than on their left (as viewed down stream), and should give indications of having migrated to the right during the thousands or millions of years of their existence. And all rivers in the southern hemisphere should give indications of having migrated to the left. Apparently no such general unidirectional migrations of old rivers have been observed by geologists.

The rotation of the Earth does cause forces on particles of water and air, which are in motion over the surface of the Earth, and these effects are very real and important. Perhaps the most commonly observed effects are those of the clockwise direction of the winds about an area of high barometric pressure, and the counterclockwise direction of the winds about a low pressure area. Similar rotational effects would be caused deep down in an ocean over which is blowing a unidirectional wind of long duration. However, in small bodies of water, the effects of the deflection-to-the-right forces (in the northern hemisphere) do not appear to be the cause of observable erosion.

Conclusions--(1) It appears that the forces which act on the water in an eddy, due to the spin of the Earth, could have caused neither the ellipticity nor the orientation of the Carolina Bays.

(2) It is clear that an eddy does not exhibit gyroscopic action.

(3) We are forced to conclude that the statement (2) we made in 1951 still seems correct, namely, "A meteorite theory of origin of the Carolina Bays appears to be the least unsatisfactory of all the theories that have been published".

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HYDROSCOPES

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(Contribution No. 767 of the Woods Hole Oceanographic Institution)

Abstract--The construction and operation are described of a device for direct observation of submerged objects in fairly clear water to depths of 30 ft.

Introduction--During World War II, a need was felt for an instrument with which one could observe submerged objects in the neighborhood of docks and other installations down to depths of approximately 30 ft. The Woods Hole Oceanographic Institution undertook the development of such a hydroscope under Contract OEMsr-31 with OSRD during the period from June, 1942, to August, 1943. The need for speed, the lack of specialized staff, and the shortages of materials precluded a thorough, refined solution of the problem, but usable instruments were designed, constructed, and tested. They were easy to handle from a rigid platform such as a dock or dam and quite manageable from a small boat in sheltered water. Calculations indicated that the length could be increased to 100 ft or more. Thus, the hydroscope appeared to be a useful instrument for those concerned with work in fairly clear water of moderate depth.

During the past ten years, there has been considerable activity in shallow-water diving with the Aqualung and in underwater photography and television, but the hydroscope does not seem to have been used appreciably. It is probable that the hydroscope has been neglected in part because its possibilities have not been well known. This brief report is being made in order to bring the instrument to the attention of those interested in underwater research.

Description of the Woods Hole hydroscope--The complete hydroscope consists of three objective sections each one meter long, one two-meter and one four-meter intermediate section, and one 3.4-meter eyepiece section, as shown in Figure 1. The three objective sections differ only in that the center of the field of view of one lies on the axis of the hydroscope tube, while in the second it is at 45° and in the third at 90° from the axis. All sections are made of 1/16-inch steel tubing 2-7/8 inches OD. One of the three objective sections and the eyepiece section are always used. The length can be increased by adding either or both of the intermediate units. The sections are joined by bolting together flanges provided with rubber gaskets to make the joints watertight.

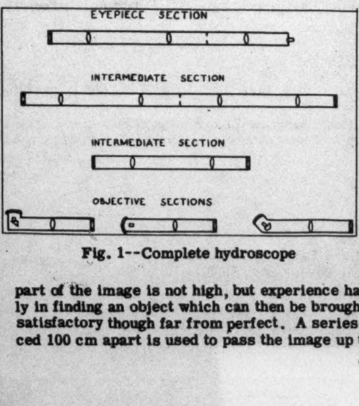

Fig. 1--Complete hydroscope

The optical system consists of an objective lens with several components which forms an image of the object being viewed, a series of achromatic lenses which pass this image up the tube, and a focusing eyepiece for viewing the final image. A good objective must (1) have a wide field of view and (2) provide rays at the image making small angles with the axis of the tube. Condition (1) is important in order that objects can be found and kept in the field of view for a reasonable time. It is particularly necessary in water containing a considerable quantity of suspended matter or when the observer is in motion. Condition (2) is, of course, essential if the light is to be confined to a long tube of small diameter. An objective meeting these requirements is shown in Figure 2. It has a total angular field in water of approximately 90°. The quality of the outer part of the image is not high, but experience has shown that the outer part of the field is used largely in finding an object which can then be brought to the center for study, and so the objective is satisfactory though far from perfect. A series of achromatic lenses with 50-cm focal lengths spaced 100 cm apart is used to pass the image up the tube. The first lens is located with its focal plane

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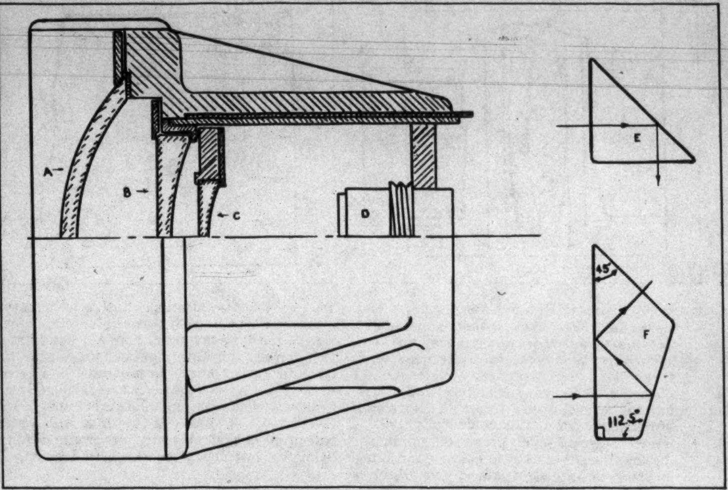

Fig. 2--Objective lens; A, window: outer radius 67 mm, inner radius 62 mm, axial thickness 5 mm, diameter 95 mm, crown glass of refractive index 1.52; B, plano-concave lens: radius 70 mm, axial thickness 3.5 mm, diameter 60 mm, crown glass of refractive index 1.52; C, plano-concave lens: radius 35 mm, axial thickness 3 mm, diameter 40 mm, crown glass of refractive index 1.52; D, Kellner eyepiece: focal length 27.4 mm, made for 7×50 binoculars; E, right-angle prism: square faces 1-1/4 inches on a side; F, prism: large face 1-1/4 by 2-1/4 inches, smaller face making an angle of 45° with the above 1-1/4 by 1-1/4 inches; the axial distances between the plane against which A is seated, the plane side of B, the plane side of C, and the plane against which the threaded part of D is pressed are 8, 12, and 62 mm; the three objective sections are obtained by using either prism E, prism F, or no prism at all.

coincident with the image formed by the objective lens. The plane waves formed by this lens are brought to focus by the second lens. This process is repeated by successive pairs of lenses. Stops with clear diameters of 1-11/16 inches are placed midway between the lenses of a pair in order to block off light which has been scattered or reflected from the walls of the tube. The arrangement of lenses, stops, and windows is shown in Figure 1. The mounting for the lenses is shown in Figure 3. It should be noted that the light passes from one section to the next as plane waves, so that the presence or absence of intermediate sections does not affect the final image in any important respect, and, in addition, the exact length of a section is not critical. A 27-mm Kellner eyepiece in a focusing mount, made for 7×50 binoculars, is used as the eyepiece. The focal lengths of the objective and eyepiece are such that the object appears slightly smaller than it would if the eye were at the window of the hydroscope. Each section is sealed with airtight glass windows in order that the tubes can be kept filled with dry air to prevent condensation and corrosion. The details of the mounting for the windows are shown in Figure 4.

Use of the hydroscope--In making observations with the hydroscope from a dock or dam, it has been found convenient to have a line attached near the lower end of the instrument. The observer holds the upper end by means of a handle clamped at right angles to the tube, while an assistant holds the line. It is sometimes suggested that strong lights can be used to 'pierce' turbid water. Actually, the suspended matter in water acts like fog and scatters the light back. Thus, strong lights usually give a loss in clarity rather than a gain. If artificial light must be used, the lamp should be kept at a distance from the window in order to illuminate as little of the water between

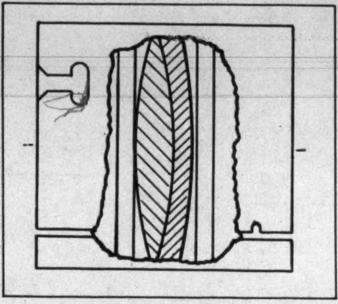

Fig. 3--Achromatic lens mounting; outside diameter is 2-3/4 inches, inside diameter 2-5/8 inches, and length 3 inches; the lens is held firmly between two split rings with three small pieces of cork; the mounting is pushed into the hydroscope tube with a tool having a crossbar that fits the T-slot shown at the upper left and its counterpart 180° away; the small notch in the slot shown at the lower right is used to hold the mounting in place; it is caught around a small screw which has been threaded through the hydroscope tube in the appropriate location and soldered in place.

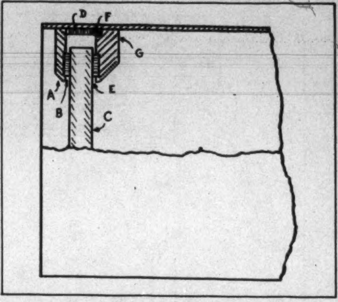

Fig. 4--Window mounting; the 1/4 inch crown glass window C is held between the rubber gaskets B and E by the brass ring A which is attached to the brass ring G by eight screws; at the same time the rubber ring F is pressed into a groove in G by the brass ring D, thus securing G to the hydroscope tube and completing the seal; a small hole through G which can be sealed with a steel ball pressed against it with a screw is used for filling the hydroscope section with dry air.

the object and the window as possible. As light at the blue end of the spectrum tends to be scattered more than that at the red end, a yellow filter is sometimes helpful.

In studying objects on the ocean bottom from a boat, the 45° objective has been valuable. A weighted line secured near the lower end of the tube can be used to control the distance between window and bottom. If a very limited region is to be studied, the boat can be anchored and its position controlled by lines. If a larger area is to be surveyed, the boat can be run against the current to give a very low speed over the ground. In either case, a camera can be mounted near the window and photographs taken when objects of interest come into view.

Various more complicated methods of operation involving adjustable vanes, motor-driven propellers, and the like have been considered. These hardly seem necessary for the 30-ft hydroscope but might be justifiable on a longer instrument.

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AN OCEANOGRAPHIC SLIDE RULE FOR COMPUTING TEMPERATURE, DEPTH, AND SALINITY

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Abstract--To simplify the processing of oceanographic data obtained at sea, a slide rule has been designed for rapid and accurate computation of temperature and depth from reversing thermometer readings, depth from wire length and wire angle, and salinity from values of temperature and electrical conductivity. The rule may be used to correct both protected and unprotected reversing thermometers, and has the advantage that individual thermometer characteristics, such as V_o and Q values and index corrections, may be recorded directly on the rule, thus eliminating the need to carry other records. Depth from thermometer readings is obtained both when Q, the pressure coefficient of the unprotected thermometer, is constant with depth, and in a special case of variable Q, hence a good estimate of depth may be made for any behavior of Q with depth. The rule also carries depth and temperature conversion scales, and has a logarithmic scale which may be used in the manner of any slide rule.

Introduction--The slide rule is designed to facilitate computation of the three basic quantities of physical oceanography, temperature, depth, and salinity. Temperature is obtained by applying corrections, found on the rule, to the reading of a protected reversing thermometer. Depth may be obtained either from the difference in the corrected readings of a protected and an unprotected reversing thermometer, or from length of wire out and wire angle at the ship. The former method is normally used for depths greater than 100 m, and the latter for shallow casts of less than 100 m [See LA FOND, 1951, for methods used heretofore]. Salinity, usually determined by chemical titration of a water sample, may also be obtained from values of the temperature and electrical conductivity of the water. The slide rule has a salinity scale based upon this relationship.

The slide rule is circular, 8-3/8 inches across, having two arms on one side and one arm on the other. The two faces are shown in Figures 1 and 2. Of the two arms shown in Figure 1, the short arm moves independently, but motion of the long arm moves both arms in such a way as to maintain a constant angle between them.

Symbols and definitions

C = correction for thermal expansion of a protected thermometer system subsequent to reversal

V_o = a constant of the individual thermometer, representing in degrees the volume of mercury below the 0° mark when the thermometer is in the reversed position at 0° Centigrade

T' = reading of the reversing thermometer, either protected or unprotected

t = reading of the auxiliary thermometer which accompanies each reversing thermometer, (that is, temperature at which reversing thermometer is read)

K = reciprocal coefficient of thermal expansion of the glass of which the thermometer is made; K is given on the certificate which accompanies each thermometer

C_u = correction for thermal expansion of an unprotected thermometer system subsequent to reversal

T_w = water temperature in situ, the corrected reading of a protected reversing thermometer

C' = value found as an intermediate step in the process of correcting an unprotected thermometer

D = depth at which the thermometers reversed

T_u = corrected reading of an unprotected reversing thermometer, a function of both temperature and pressure

ρ_m = mean density of the water column above the level of reversal

Q = pressure coefficient of the individual unprotected thermometer, expressed in degrees Centigrade increase in the reading per 0.1 kg/cm^2 increase in pressure

Wire length = length of wire from sea surface to water bottle

Wire angle = angle which the wire makes with the vertical at the ship

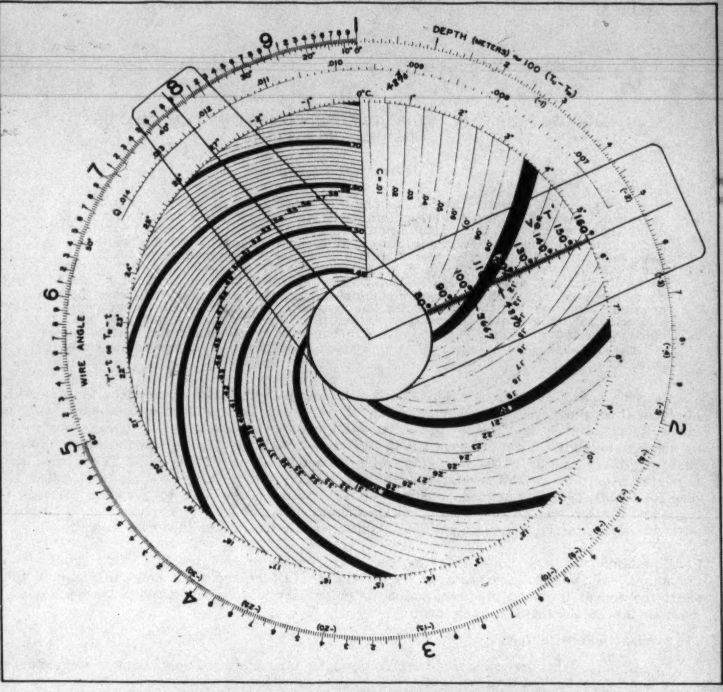

Fig. 1--Thermometer corrections and depth are determined on this side of rule; by writing thermometer numbers beside the appropriate points of the scales, as shown, the V_0 values of all thermometers may be recorded on the long arm, and the Q values of all unprotected thermometers may be recorded along the Q scale

Correction of reversing thermometer readings--The change in the reading of a protected reversing thermometer due to a change in temperature conditions subsequent to reversal may be expressed by an equation derived by SVERDRUP [1947] for protected thermometers:

$$C = (V_0+T')(T'-t)/[K-(V_0+T')-(T'-t)]$$

This is the correction which must be applied to the reading to obtain the reading at reversal in the sea.

The quantity K is a characteristic of the glass of which the thermometer is made, and for most thermometers has the value 6100, hence this constant value has been used in the construction of the rule. If, for either a protected or an unprotected thermometer, K has the value 6300, the thermal expansion correction C or C_u obtained from the slide rule should be reduced by about three per cent of its value. This reduction amounts to 0.01° C in the range 0.16° to 0.47° C, and 0.02° C for greater corrections.

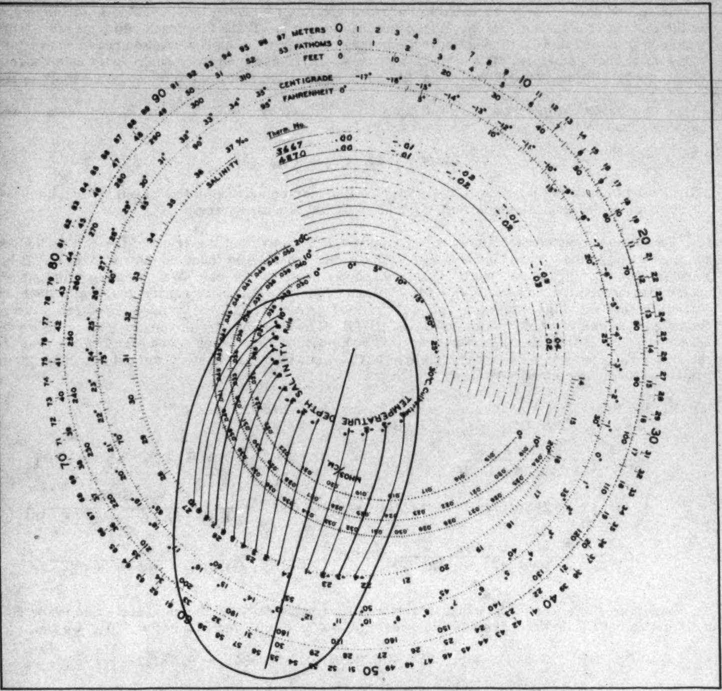

Fig. 2--Salinity is determined on this side of rule; also shown are conversion scales for depth and temperature, and a blank, semi-circular table where individual thermometer index corrections may be entered at appropriate temperatures for as many as 15 thermometers

If each expression in parentheses in the above equation be considered as a unit, the equation contains three variables, C, (V_0+T'), and $(T'-t)$. The striped graph shown in Figure 1 is a protected thermometer correction graph, giving the correction C in the body of the graph as a function of (V_0+T') on the radial scale and $(T'-t)$ on the circular scale. In plotting the stripes, negative values of C were used, for $(T'-t)$, and therefore C, are usually negative. Positive values of $(T'-t)$ are always small, and the graph is entirely satisfactory for both positive and negative values.

The rule is entered directly with the raw data T′ and t. By setting the two arms to these values on the linear scale surrounding the striped graph, the difference $(T'-t)$ is automatically measured off along this scale. If the long arm is set to the larger of the two temperatures, subsequent rotation of the long arm until the short arm is at 0° brings the scale of the long arm into position for reading the correction C beneath the value (V_0+T') on the long arm. To eliminate mental addition of V_0 and T′, part of the long arm has been frosted so thermometer numbers may be entered beside their V_0 values on the scale. Thus, counting T′ degrees up the scale from the V_0 point, the thermal expansion correction C is obtained.

A second correction to be added to the reading of the reversing thermometer is for any error in the etching of its scale. On the side of the rule shown in Figure 2, a blank semi-circular table has been provided in which index corrections may be entered at appropriate temperatures for as many as 15 thermometers. The table is so placed that the temperature scale at its inner edge corresponds with the scale of meters at the outer edge of the rule, which is perhaps easier to read.

For unprotected thermometers the correction derived by SVERDRUP [1947] for thermal expansion subsequent to reversal is expressed by

$$C_u = (V_o + T')(T_w - t)/[K - (T_w - t)]$$

With a slight change in procedure, the protected thermometer graph of the rule may also be used to determine the expansion correction for unprotected thermometers.

From the protected thermometer equation it will be noted that the graph of the rule is the graph of an equation of the general form $C = AB/(K - A - B)$, where A is found on the radial scale, B is found on the circular scale, and C represents the value of the stripes. When dealing with unprotected thermometer data we let $(V_o + T') = A$ and $(T_w - t) = B$. Entering the graph with these variables we read from the stripes a value $C' = AB/(K - A - B)$. But the desired unprotected thermometer correction, as shown above, is $C_u = AB/(K - B)$. If on the circular scale of the rule we subtract the value C' from B, and enter the graph again with the variables A and $(B - C')$, we read from the stripes a value which is extremely close to C_u, and which may be used without error for the unprotected thermometer correction.

Let the final correction obtained in this manner be called C''; then $C'' = A(B - C')/[K - A - (B - C')]$. Since $C' = AB/(K - A - B)$

$$C'' = \frac{AB - A^2B/(K - A - B)}{K - A - B + AB/(K - A - B)} = [AB(K - A - B) - A^2B]/[(K - A - B)^2 + AB]$$

$$= AB(K - B - 2A)/[(K - B - A)^2 + AB] = [AB/(K - B)]\frac{(K - B - 2A)}{[K - B - 2A + (A^2 + AB)/(K - B)]}$$

$$= C_u\frac{(K - B - 2A)}{[K - B - 2A + (A^2 + AB)/(K - B)]} = C_u\frac{1}{[1 + (A^2 + AB)/(K^2 - 2BK - 2AK + B^2 + 2AB)]}$$

Evaluating the error in the expansion correction for unprotected thermometers due to the use of C'' instead of C_u, in the extreme case where $(V_o + T') = 160°$ and $(T_w - t) = -30°C$ we find

$$C'' = C_u[1/(1 + 20{,}800/35{,}615{,}300)] = 0.78303\ (1/1.000584) = 0.78257$$

The greatest possible difference between C'' and C_u is less than 0.0005°C. Since the correction is desired only to the nearest 0.01°C, such an error is negligible.

Along any radial line on the graph of the rule the width of the stripes is very nearly constant. This fact makes possible the extrapolation of values of the correction beyond the graph in case the value of $(V_o + T')$, for either a protected or an unprotected thermometer, is so large that it runs off the scale. The procedure is to use $1/2\,(V_o + T')$ and double the value of the correction found.

Depth determination from reversing thermometer readings--The equation used for determining depth of thermometer reversal from the corrected readings of the protected and unprotected thermometers, derived by WÜST [1933], is

$$D = (T_u - T_w)/\rho_m Q$$

The Q value of an unprotected thermometer is generally considered to be a constant. However, in determining depth on the slide rule, depth is first found assuming that the product $\rho_m Q$ is a constant. A small correction is then applied to obtain depth when Q is constant.

The scales involved in the depth determination are the outer logarithmic scale, the short Q scale, and the scale of figures in parantheses around the inner side of part of the logarithmic scale. The Q scale is a reciprocal logarithmic scale shifted to the left relative to the outer logarithmic scale by the amount 1/1.0294, where 1.0294 is an average value of ρ_m at a depth of 1000 m. Each value of Q on the Q scale is in line with the value 1/1.0294Q on the outer logarithmic scale.

In order to distinguish between them, let the symbol D represent the depth obtained when Q is a constant, and let D′ represent the depth obtained when the product $\rho_m Q$ is a constant. It is evident that D′ is directly proportional to the temperature difference $(T_u - T_w)$. Assuming that the value given for Q is correct at a depth of around 1000 m (that is, where $\rho_m = 1.0294$), the depth D′ is obtained on the outer logarithmic scale of the rule by multiplication of the factors $(T_u - T_w)$ and 1/1.0294Q, the latter found by setting to Q on the Q scale.

The difference between the depths D and D′ is effectively a function of depth alone, as shown by the computation

$$T_u - T_w = \rho_m QD = 1.0294\,QD'$$

$$D = (1.0294/\rho_m)\,D'$$

$$D - D' = (1.0294/\rho_m - 1)\,D'$$

At any depth D, the value of ρ_m is known. Therefore, the difference (D - D′) is a known function of D′. Having determined D′ on the slide rule, the depth D may be found by applying the small correction (D - D′). The figures in parentheses adjacent to the logarithmic scale are values of (D - D′) for depths greater than 1000 m, and are placed at appropriate values of D′ on the logarithmic scale. It will be noted that the values are negative, for at depths greater than 1000 m D′ is greater than D. At depths of less than 1000 meters D′ is less than D by somewhat less than one meter (see Table 1). To obtain D in shallow depths, if D′ is between 200 and 800 m, add one meter.

In order to compute the scale of (D - D′) it was necessary to assume an average distribution of ρ_m with depth. The values computed by WÜST [1933] for the North Atlantic Ocean were used. Accuracy of the values is not critical, and even in localities where the density distribution is fairly extreme, use of Wüst's values will give an error in depth rarely as great as one meter at any depth.

The first three columns of Table 1 indicate how the scale of (D - D′) was obtained. In the first column are standard values of depth, in meters. In the second column are corresponding values of ρ_m as determined by Wüst for the North Atlantic. The third column gives D′ as computed from the equation $D' = D\rho_m/1.0294$. Values of (D - D′) are found from columns 1 and 3. To find D′ at unit values of (D - D′), for placing the scale on the rule, corresponding values were plotted on a large graph, a smooth curve drawn, and the desired data read from the curve. The last two columns of Table 1 are included only for comparison, to show the relative unimportance of any particular density distribution to the computation of depth.

Table 1--D and D′ for given values of mean density ρ_m

D	Averages for North-Atlantic (Wüst)		Typical for water of low salinity	
	ρ_m	D′	ρ_m	D′
m	gm/cm³	m	gm/cm³	m
100	1.0262	99.7	1.0248	99.6
200	1.0267	199.5	1.0255	199.2
300	1.0271	299.3	1.0261	299.0
400	1.0275	399.3	1.0267	399.0
500	1.0278	499.2	1.0272	498.9
600	1.0282	599.3	1.0276	599.0
700	1.0285	699.4	1.0280	699.0
800	1.0288	799.5	1.0283	799.1
900	1.0291	899.7	1.0286	899.3
1000	1.0294	1000.0	1.0289	999.5
1500	1.0308	1502.0	1.0304	1501.5
2000	1.0321	2005.2	1.0318	2004.7
2500	1.0334	2509.7	1.0331	2509.0
3000	1.0346	3015.2	1.0344	3014.6
3500	1.0358	3521.8	1.0356	3521.1
4000	1.0370	4029.5	1.0369	4029.1

To facilitate the depth computation, and also to provide a convenient record of Q values, a section below the Q scale on the slide rule is frosted to permit written entries of unprotected thermometer numbers beside their Q values. It has been assumed that the value given for Q is correct at the depth where $\rho_m = 1.0294$. If Q is a constant, this is of course true. If Q is believed to be a variable, varying in such a way that $\rho_m Q$ remains constant, and its value has been determined at another depth, its value at $\rho_m = 1.0294$ for use on the slide rule may be obtained by dividing the known constant value of $\rho_m Q$ by 1.0294.

Since the slide rule gives depth both for the case where Q is a constant and for the special case where Q decreases with depth in inverse proportion to ρ_m, a good estimate of depth may be obtained for any known behavior of Q with depth. For example, if Q should increase with depth at the same rate as ρ_m, the correction to D′ would be twice as great as for Q constant.

Depth determination from wire length and wire angle--This method of depth determination is used for shallow casts, when it can be assumed that the wire is reasonably straight in the water. The slide rule scales used are the logarithmic scale and the contiguous scale of wire angles, shown in Figure 1. Each wire angle is placed at its cosine on the logarithmic scale. Depth is obtained on the logarithmic scale by multiplying wire length (below sea surface) by cosine of wire angle, the latter found by setting directly to the angle on the wire angle scale.

Salinity determination from temperature and conductivity--The salinity section of the rule, shown in Figure 2, is based upon the work of THOMAS, THOMPSON and UTTERBACK [1934], who determined the electrical conductivity of sea water as a function of its chlorinity for the six temperatures 0°, 5°, 10°, 15°, 20°, and 25°C. Since chlorinity and salinity are related, a table could be constructed from the above data which gave salinity as a function of conductivity at each of the six temperatures. Table 2 presents a small portion of this table. The salinity differences at constant conductivity through 5° temperature increases from 0°, 10° and 20° were computed and entered in the table as shown.

Table 2--Simplified portion of a table giving salinity as a function of conductivity for the six temperatures at which it was known; the salinity differences between isothermal columns have been entered as needed

Conductivity	0°	Sal. diff.	5°	10°	Sal. diff.	15°	20°	Sal. diff.	25°
0.025	29.70	4.32	25.38	22.00	2.72	19.28	17.06	1.83	15.23
0.026	31.00	4.51	26.49	22.96	2.84	20.12	17.81	1.92	15.89
0.027	32.31	4.70	27.61	23.94	2.97	20.97	18.56	2.00	16.56
0.028	33.63	4.90	28.73	24.91	3.08	21.83	19.32	2.08	17.24
0.029	34.95	5.09	29.86	25.89	3.20	22.69	20.08	2.16	17.92
0.030	36.28	5.28	31.00	26.88	3.33	23.55	20.84	2.24	18.60

The salinity portion of the rule is essentially a circular graph, where the circular coordinate is salinity, and the radial coordinate is salinity decrease per 5° temperature increase at constant conductivity (the difference columns of Table 2). The radial scale was made logarithmic in order to keep the three isotherms from crowding at one end. For better illustration, Figure 3 shows the salinity part of the rule in rectangular form.

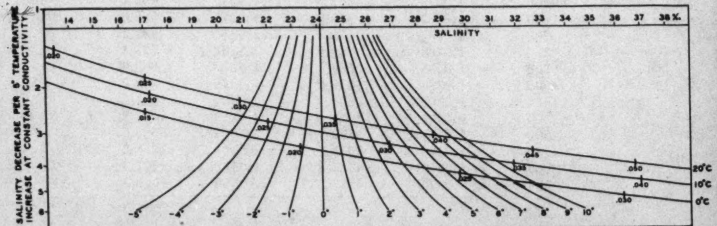

Fig. 3--The salinity graph and arm of the slide rule in rectangular form

The three isotherms were constructed by plotting points at corresponding values of salinity and salinity difference to the isotherm 5° higher, and the conductivity value was entered beside each point. It will be noted that lines of constant conductivity (not drawn) slope upward to the left through the isotherms. Every point of the graph represents a definite value of all three variables, temperature, conductivity, and salinity.

The lines of the arm represent temperature increments for use in interpolating between the isotherms of the graph, such that when a line of the arm is placed on an isotherm at a given conductivity, the straight line of the arm passes through the unmarked point of the graph which represents that conductivity and the sum of the two temperatures. The desired salinity is then read under the straight line on the scale above.

Each temperature increment line must be so placed on the arm that any point at which it crosses an isotherm is distant from the straight line by the salinity difference through the required temperature interval at the conductivity of that point of the isotherm. For example, in Figure 3 the 4° line of the arm crosses the 10° isotherm at a conductivity of 0.030 mhos/cm. The distance, measured in salinity on the salinity scale, between this point of the 4° line and the straight line is the salinity difference between 10° and 14° at a conductivity of 0.030 mhos/cm. But, as the arm moves across the graph, this distance should also be the salinity difference between 0° and 4° at a conductivity of 0.0196, and the salinity difference between 20° and 24° at a conductivity of 0.0429 mhos/cm. This is very nearly true, but not quite. It is inherent in the nature of the graph that only one line of the arm besides the straight 0° line could be made absolutely accurate with respect to all three isotherms of the rule. The selection of the ordinate scale designates the 5° line as having this property, for all three isotherms were plotted against this ordinate scale. Note that the salinity difference from any point of the 5° line to the straight line is also equal to the ordinate of the point. The other lines of the arm could be accurately placed for application to one of the isotherms of the rule, but not all three. They have been made accurate, as nearly as possible, for application to the 10° isotherm of the rule, except for the lower, off-set portions of lines 6° to 10°, which are accurate as applied to the 0° isotherm of the rule.

In order to construct the lines of the arm, it was necessary to find the salinity difference at constant conductivity between any two temperatures. This was done graphically by plotting against a temperature scale the known 5° salinity differences for each conductivity, and drawing smooth curves. The results, read from the curves, were checked for smoothness by a numerical difference method. Thus the salinity differences from each of the three isotherms 0°, 10°, and 20° to every other desired temperature were tabulated at each value of conductivity.

The arm of the rule was then plotted on a large rectangular graph similar to that of Figure 3 except that both coordinates were linear. To construct lines accurate with respect to the 10° isotherm, the salinity differences through each integral temperature increment from 10° were plotted against the salinity difference through a 5° temperature increase from 10° (the ordinate scale) at each value of conductivity. On this graph the 0° and 5° lines were of course straight. The 10° and -5° lines, which could be plotted from original data, were so nearly perfectly straight that it was believed all lines should be made straight. This provided a further check on the accuracy of the salinity differences determined graphically. Final values for plotting the arm of the rule against a logarithmic scale (see Fig. 3) were taken from this graph.

The lines of the arm thus designed for application to the 10° isotherm of the rule give accurate readings of salinity throughout the temperature range 5° to 20°C. Moreover the 0° and 5° lines of the arm are accurate as applied to all three isotherms of the rule. To determine the error involved when the other lines of the arm are applied to the 0° and 20° isotherms of the rule, the procedure outlined in the preceding paragraph was repeated using temperature increments from 0° and 20° respectively, and the corresponding lines drawn. If the lower portions of lines 6° to 10° on the arm, which do not cross the 10° isotherm of the rule, were made accurate with respect to the 0° isotherm, it was found that the error in the salinity reading could be kept within 0.02 °/oo over the entire temperature range -2° to 27°C.

Owing to construction difficulties, the present slide rule does not give the accuracy of which a salinity rule of this type is capable, as indicated above. The scales are poorest at temperatures below 5°C. Although much more accurate in most of the range, it is believed safe to say that the present rule is accurate to within 0.10 °/oo of salinity over the temperature range -2° to 27°C. The great advantage of a rule of this type is simplicity of operation, for salinity is found with but a single setting.

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ON THE DETERMINATION OF FREQUENCY FACTOR IN LOG-PROBABILITY PLOTTING

Ven Te Chow

The purpose of this note is to revise the procedure of transformation of the variate in the logarithmically normal probability (abbreviated hereafter as log-probability) discussed in the Transactions [Chow, 1952]. The correct procedure and the resulting expressions for determining the frequency factor of the log-probability plotting should be developed as follows:

Let $y = \log_e x$, then y is normally distributed and the frequency function of y is

$$f(y) = (1/\sqrt{2\pi\sigma_y}) \exp[-(y-\bar{y})^2/2\sigma_y^2] \quad \ldots \ldots \ldots \ldots \quad (1)$$

in which $\bar{y} = \overline{\log_e x}$ and $\sigma_y = \sigma_{\log_e x}$ are respectively the mean and standard deviation of y, and e is the base of natural logarithms. A typical example of this distribution is shown on the top of Figure 1. The dotted lines indicate the variate y in rectangular scale. The variate x is shown in natural log-scale. It is apparent that y is normally distributed, being symmetrical with respect to the mode.

From the standard transformation formula of statistical mathematics, or

$$\emptyset(x) = f(y)\,\left| dy/dx \right| \quad \ldots \ldots \ldots \ldots \ldots \quad (2)$$

in which $dy/dx = e^{-y} = 1/x$, the frequency function of x is

$$\emptyset(x) = (1/\sqrt{2\pi}\, x\sigma_{\log_e x}) \exp[-(\log_e x - \overline{\log_e x})^2/2\sigma^2_{\log_e x}] \quad \ldots \ldots \quad (3)$$

or

$$\emptyset(x) = (1/\sqrt{2\pi}\, e^y \sigma_y) \exp[-(y-\bar{y})^2/2\sigma_y^2] \quad \ldots \ldots \ldots \ldots \quad (4)$$

Eq. (3) represents the frequency function of the log-probability law. A typical example of the distribution of this law is shown on the top of Figure 2 in which the variate x is shown in rectangular scale. It shows that the distribution of x is asymmetrical. As the value of y in the symmetrical normal distribution as shown in Figure 1 ranges from $-\infty$ to ∞, the corresponding value of x in the asymmetrical distribution as shown in Figure 2 ranges from 0 to ∞.

The rth moment for the log-probability distribution (3) takes the form

$$M_r = \int_0^\infty x^r\, \emptyset(x)\, dx \quad \ldots \ldots \ldots \ldots \ldots \quad (5)$$

The transformation of (5) from x-scale to y-scale may be done by the standard transformation formula (2), or the relation $\emptyset(x)\, dx = f(y)\, dy = dP$ as shown in Figures 1 and 2. Then, the rth moment in y-scale becomes

$$M_r = \int_{-\infty}^\infty x^r f(y)\, dy \quad \ldots \ldots \ldots \ldots \ldots \quad (6)$$

Since $y = \log_e x$ or $x = e^y$ and $f(y)$ is represented by (1), (6) appears as

$$M_r = (1/\sqrt{2\pi}\,\sigma_y)\int_{-\infty}^\infty \exp[ry - (y-\bar{y})^2/2\sigma_y^2]\, dy \quad \ldots \ldots \ldots \quad (7)$$

Completing the square, the exponent of e becomes

$$\begin{aligned} ry - (y-\bar{y})^2/2\sigma_y^2 &= -(1/2\sigma_y^2)(y - r\sigma_y^2 - \bar{y})^2 + (r\bar{y} + r^2\sigma_y^2/2) \\ &= -z^2/2 + (r\bar{y} + r^2\sigma_y^2/2) \quad \ldots \ldots \ldots \ldots \quad (8) \end{aligned}$$

where $z = (1/\sigma_y)(y - r\sigma_y^2 - \bar{y})$ from which $dy = \sigma_y dz$. Substituting this expression for dy

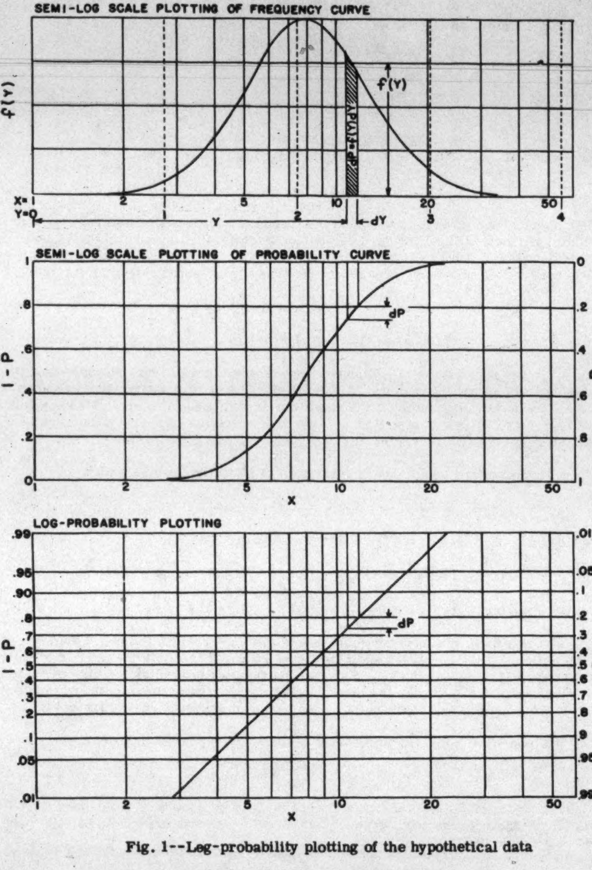


Fig. 1--Log-probability plotting of the hypothetical data

and the expression of (8) for the exponent in (7), the rth moment is

$$M_r = (1/\sqrt{2\pi})\exp[\,r\overline{y} + r^2\sigma_y^2/2\,]\int_{-\infty}^{\infty} e^{-z^2/2}\,dz \; \ldots\ldots \quad (9)$$

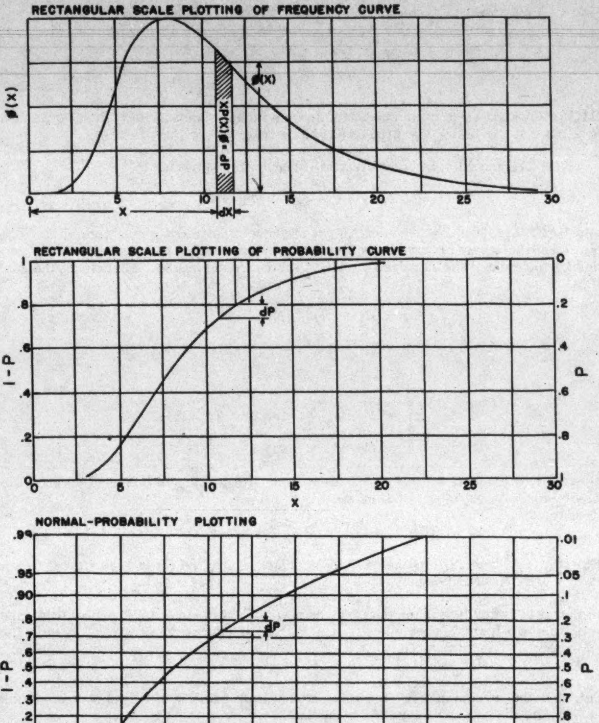
Since $(1/\sqrt{2\pi})\int_{-\infty}^{\infty} e^{-z^2/2}\,dz = 1$, the rth moment becomes

$$M_r = \exp[\,r\overline{y} + r^2\sigma_y^2/2]. \ldots\ldots\ldots\ldots \quad (10)$$

Assigning the value of r = 0, 1, 2, and 3, the first four moments are

$$M_0 = 1 \; \ldots\ldots\ldots\ldots \quad (11)$$

$$M_1 = \exp[y + \sigma_y^2/2] \; \ldots\ldots\ldots\ldots \quad (12)$$


RECTANGULAR SCALE PLOTTING OF FREQUENCY CURVE

RECTANGULAR SCALE PLOTTING OF PROBABILITY CURVE

NORMAL-PROBABILITY PLOTTING

Fig. 2--Normal probability plotting of the hypothetical data

$$M_2 = \exp[2\overline{y} + 2\sigma_y^2] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (13)$$

$$M_3 = \exp[3\overline{y} + (9/2)\sigma_y^2] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (14)$$

The mean, $\overline{x}$, the standard deviation, σ_x, and the skewness, α_x, of x are computed as follows

$$\overline{x} = M_1/M_o = \exp[\overline{y} + \sigma_y^2/2] \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

$$\sigma_x = [(M_2 M_o - M_1^2)/M_o^2]^{1/2}$$

$$= (e^{\sigma_y^2} - 1)^{1/2} \exp[\bar{y} + \sigma_y^2/2] \qquad (16)$$

and

$$\alpha_x = (M_3 M_o^2 - 3M_2 M_1 M_o + 2M_1^3)/M_o^3$$
$$= (e^{3\sigma_y^2} - 3e^{\sigma_y^2} + 2) \exp[3\bar{y} + (3/2)\sigma_y^2] \qquad (17)$$

Eq. (15), (16), and (17) are the conditions for the mean, standard deviation, and skewness respectively such that the law of log-probability holds true.

From (15) and (16) the coefficient of variation is expressed by

$$C_v = \sigma_x/\bar{x} = (e^{\sigma_y^2} - 1)^{1/2} \qquad (18)$$

By HAZEN [1930, p. 44] the coefficient of skew is defined as 'the sum of the cubes of the variations of the terms of the series divided by the number of terms less one and the quotient divided by the cube of the standard variation (standard deviation).' Therefore, the coefficient of skew is

$$C_s = \Sigma(x - \bar{x})^3/(N - 1)\sigma_x^3$$
$$= (\overline{x^3} - 3\overline{x^2}\bar{x} + 2\bar{x}^3)/[(N - 1)/N]\sigma_x^3 \qquad (19)$$

in which

$$\overline{x^2} = M_2/M_o = \exp[2\bar{y} + 2\sigma_y^2] \qquad (20)$$

$$\overline{x^3} = M_3/M_o = \exp[3\bar{y} + (9/2)\sigma_y^2] \qquad (21)$$

Substituting (15) for $\bar{x}$, (20) for $\overline{x^2}$, (21) for $\overline{x^3}$, and (16) for σ_x in (19), and taking N as infinity, the expression for the coefficient of skew becomes

$$C_s = (e^{3\sigma_y^2} - 3e^{\sigma_y^2} + 2)/(e^{\sigma_y^2} - 1)^{3/2} \qquad (22)$$

Eq. (15, (18), and (22) may be used to calculate $\bar{x}$, C_v, and C_s of the original items of x, when values of $\bar{y}$ and σ_y are given.

It should be noted that if the data plot on a straight line on the log-probability paper as shown on the bottom of Figure 1, then $\bar{y} = \overline{\log_e x} = \log_e M$, or expressed in the exponential form

$$M = e^{\bar{y}} \qquad (23)$$

in which M is the median of x, or the value of x at a probability of 50 pct of time. Substituting (23) in (15), the ratio of the mean to the median is

$$\bar{x}/M = e^{\sigma_y^2/2} \qquad (24)$$

Now, as the expressions indicate, the characteristic values of the log-probability law: $\bar{x}/M$, C_v, and C_s are functions of σ_y only. LANGBEIN [1946, p. 710] has prepared curves showing these values plotted against σ_g which is equal to e^{σ_y}. However, his curve for C_s is approximate as it is based on the approximate logarithmic skew curve factors developed by HAZEN [1930, p. 188].

As mentioned in the previous discussion, the value of index of variability, I_v, proposed by LANE and LEI [1950] is theoretically equivalent to σ_y. Since I_v is obtained usually from the log-probability paper in which the common logarithm is employed, while σ_y is computed on the basis of the natural logarithm, the relation between I_v and σ_y is

$$\sigma_y = (\log_e 10)\, I_v = 2.3026\, I_v \qquad (25)$$

$$I_v = (\log_{10} e)\, \sigma_y = 0.4343\, \sigma_y \qquad (26)$$

When the value of I_v is given, the value of σ_y may be computed by (25), and the characteristic values of the log-probability plotting for x may be calculated by the derived (18), (19), and (24).

Considering $C_s = 1$ and solving (22) for $e^{\sigma_y^2}$, the real root which forms a distribution is $e^{\sigma_y^2} = 1.105$. Then, $\sigma_y = 0.316$, and from (15), $\bar{y} = \log_e(\bar{x}/1.051)$. By (18), $C_v = 0.324$.

The computation of the frequency factor K for the log-probability plotting, when $C_s = 1$, may proceed as follows. Let

$$K_y = (y - \bar{y})/\sigma_y \quad (27)$$

Substituting the computed value of σ_y and $\bar{y} = \log_e(\bar{x}/1.051)$ in (27) and simplifying

$$x/\bar{x} = 1 + (e^{0.316K_y}/1.051 - 1) \quad (28)$$

Comparing this equation with the general formula for hydrologic frequency analysis [CHOW, 1951] we see that

$$C_vK = e^{0.316K_y}/1.051 - 1 \quad (29)$$

Since $C_v = 0.324$, the frequency factor is

$$K = (e^{0.316K_y}/1.051 - 1)/0.324 \quad (30)$$

From (27), $K_y = (y - \bar{y})/\sigma_y$ and $dy = \sigma_y dK_y$. Substituting these terms in (1), the probability equal to or greater than the given magnitude of the variate is given by

$$P = \int dP = \int_{K_y}^{\infty} f(y)\,dy = (1/\sqrt{2\pi})\int_{K_y}^{\infty} e^{-K_y^2/2}\,dK_y \quad (31)$$

which is equal to the area under the normal probability curve and above the horizontal axis for the variate ranging from K_y to ∞. Eq. (31) may be evaluated by the aid of any standard table for the normal probability function. The probability equal to or less than the given value is therefore equal to 1-P and the value of P is equal to the reciprocal of the recurrence interval, T. By (30) and (31), and the relation between P and T, the K-values for given values of P or T are computed as shown in Table 1. Except for very small values of P, the computed theoretical frequency factors are in excellent agreement with Hazen's revised approximate factors. However, further computations indicate that appreciable discrepancy exists for high coefficients of skew, at which Hazen's factors are greater than the theoretical values.

Table 1--Computation of K-values for log-probability plotting, when $C_s = 1$

Frequency			K_y by (31)	$0.316K_y$	$e^{0.316K_y}$	K by (30)	Hazen's revised approx. factor
1-P	P	T					
pct	pct	year					
1	99	1.01	-2.327	-0.735	0.479	-1.68	-1.69
5	95	1.05	-1.645	-0.520	0.596	-1.34	-1.34
20	80	1.25	-0.842	-0.266	0.767	-0.84	-0.84
50	50	2	0	0	1.000	-0.15	-0.15
80	20	5	0.842	0.266	1.305	0.75	0.76
95	5	20	1.645	0.520	1.680	1.85	1.90
99	1	100	2.327	0.735	2.085	3.03	3.15
99.9	0.1	1000	3.090	0.976	2.659	4.72	4.92

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CALCULATING THE DISTANCE BETWEEN EQUIVALENT POLES OF A BAR MAGNET

James R. Boggs

It is assumed that the field of a bar magnet, as observed at a given exterior point P, may be interpreted as though it arose entirely from two point poles situated on the axis of the bar, and equidistant from its center. The problem here discussed is to find L, the separation of these equivalent poles, when the direction of the field at P is known.

In Figure 1, the field vector at P is represented by PH. It may be resolved into components PH_1 due to equivalent pole N, and PH_2 due to S. PH is extended to point T on the axis of the magnet. The figure defines the angles A, D, ϕ, θ, the distances r, r_1, r_2, t, and the magnitudes h, h_1, and h_2. The observed quantities are ϕ, θ, and r.

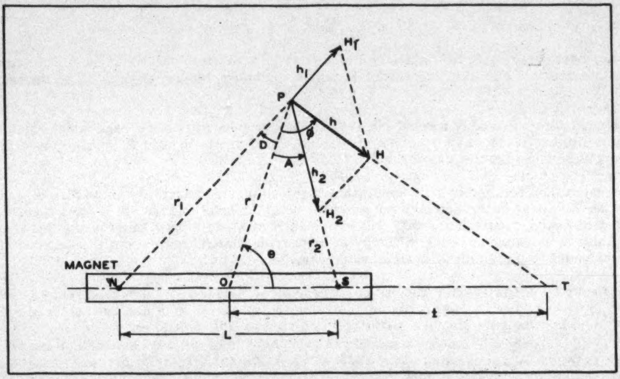

Fig. 1--Resolution of field ascribed to equivalent poles

In triangle PHH_2, angle PHH_2 is the supplement of $(\phi+D)$ and hence by the law of sines we have

$$h_2/h_1 = \sin(\phi+D)/\sin(\phi-A) \quad \text{- - - - - - - - - - - - - (1)}$$

Again applying the law of sines in triangles NPT and SPT,

$$[r_1 \sin(\phi+D)]/(t+L/2) = \sin(\phi+\theta) = [r_2 \sin(\phi-A)]/(t-L/2) \quad \text{- - - - (2)}$$

Dropping the interior member of (2), the rest can be used to remove the functions in the right-hand member of (1), yielding

$$h_2/h_1 = r_2(1+KM)/r_1(1-KM) \quad \text{- - - - - - - - - - - - (3)}$$

where

$$K = L/2r \quad \text{- (4)}$$

and

$$M = r/t$$

$$= \sin(\phi+\theta)/\sin\phi = \cos\theta + \sin\theta \cot\phi \text{ - - - - - - } (5)$$

Now, by Coulomb's law for point magnetic poles

$$h_2/h_1 = r_1^2/r_2^2 \text{ - - - - - - - - - - - - - - - - - - } (6)$$

Combining (3) and (6) so as to eliminate h_2/h_1, we have

$$r_1^3/r_2^3 = (1+KM)/(1-KM) \text{ - - - - - - - - - - - - - - - } (7)$$

Next, utilizing the law of cosines in triangles NPO and SPO

$$(1+K^2+2K\cos\theta)/r_1^2 = 1/r^2 = (1+K^2-2K\cos\theta)/r_2^2 \text{ - - - - - - - - - - } (8)$$

Dropping the interior member of (8), the rest can be used to eliminate r_1 and r_2 from (7), yielding

$$(1-KM)^2(1+K^2+2K\cos\theta)^3 = (1+KM)^2(1+K^2-2K\cos\theta)^3 \text{ - - - - - } (9)$$

Expanding, collecting terms, and dividing by 12K cos θ, we find

$$(M^2-N/3)K^6+(FM^2-EN+1)K^4+(M^2-EN+F)K^2-N/3+1 = 0 \text{ - - - - } (10)$$

where $E = 1+4\cos^2\theta$, $F = (1/3)(E+5)$, and $N = M\sec\theta$.

In any particular case, the values of θ and ϕ can be utilized to write (10) as a cubic equation in K^2 with numerical coefficients, whence K can be evaluated, leading through (4) to the value of L.

Editorial note--Probably no real magnet can be represented by such 'equivalent poles' except in a highly limited sense. Nevertheless, the present exercise is thought to be of interest in view of historical reliance on the pole concept.

The use of (10) for finding pole separation requires a rather accurate knowledge of ϕ, since it relies on the slight difference between ϕ for the actual magnet and the value for a theoretical dipole (infinitesimal pole separation). The uncertainty of ϕ would have an influence that increases with r, while at the same time the difficulty of measuring ϕ would increase with r because the ambient field would be increasingly difficult to circumvent.

If sufficiently accurate observations of ϕ are made at various positions, the results can be used in (10) to show how the separation of equivalent poles varies as P moves about. BLAKESLEY [1891] showed how the pole distance might be calculated for the special case $(\theta+\phi) = 90°$. When $\theta = 90°$ or 0°, clearly ϕ is independent of L. Measurements of the field strength at any two such points will yield a pole separation (Gray 1893, p. 85; Starling 1929, p. 26) but this result has a significance unlike that of the present L.

A quite different method of finding equivalent poles [MASUMOTO, ÔTOMO, and SUGIHARA, 1953] makes use of the distribution of leakage flux as observed with a search coil. ---D. G. K.

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REPORT OF THE COMMITTEE ON THE PHYSICS OF SOIL MOISTURE, 1952-1953, CONCLUSION

G. B. Bodman, Chairman

J. E. Christiansen   J. R. McHenry   J. S. Robins
R. M. Hagan   R. D. Miller   C. M. Woodruff

The first part of the Committee's Report appeared in December 1953 issue of the Transactions, pages 938-944. Attention was there directed to a second part of the Report to appear later. It was stated that this would consist of a paper by F. J. Veihmeyer and A. H. Hendrickson: Does Transpiration Decrease as the Soil Moisture Decreases? This paper was presented before the Section of Hydrology on May 4, 1953.

After reading all contributions here presented upon the question provided by the title of the paper itself, it is evident that wide differences of opinion prevail concerning the answer. The Chairman of the Committee will simply point out that there may be two possible explanations of these differences: (1) all participants are not, in actual fact, considering precisely the same phenomenon, and (2) the phenomenon under discussion has not, in all cases cited in support, been directly measured.

The paper, together with invited comments from others and a reply by the authors, appears on pages 425-448 of this issue.

LETTERS TO THE EDITOR

CORRECTIONS TO A SOLUTION CONCERNING HYDROLOGIC FREQUENCY ANALYSIS

Reference is made to the paper by Ven Te Chow entitled 'A General Formula for Hydrologic Frequency Analysis' [Trans., v. 32, no. 2, pp. 231-237, 1951] and to the discussion of this paper by E. J. Gumbel and Ven Te Chow [Trans., v. 33, no. 2, pp. 277-282, 1952]. The purpose of this letter is to correct some errors in Chow's solution in the discussion. Assuming that the variable x is log-normally distributed, we have

$$P = (1/\sqrt{2\pi}\,\sigma_y)\ \exp[-(y-\bar{y})^2/2\sigma_y^2] \qquad (25)$$

in which $y = \log_e x$, or

$$P = (1/\sqrt{2\pi}\,\sigma_{\log_e x})\ \exp[-(\log_e x - \overline{\log_e x})^2/2\sigma_{\log_e x}^2] \qquad (26)$$

for which, $0 \leq x \leq \infty$. Then, the rth moment about 0 of x is

$$M_r = \int_0^\infty P x^r\,dx = \exp[\,r\,(2\bar{y} + r\sigma_y^2)/2\,] \qquad (27)$$

and the first four moments of x are

$$M_0 = 1 \quad \text{(as could be expected)} \qquad (28)$$

$$M_1 = e^{\bar{y} + \sigma_y^2/2} \qquad (29)$$

$$M_2 = e^{2\bar{y} + 2\sigma_y^2} \qquad (30)$$

$$M_3 = e^{3\bar{y} + (9/2)\sigma_y^2} \qquad (31)$$

Then we have

$$\bar{x} = e^{\bar{y} + \sigma_y^2/2} \quad (32)$$

$$\sigma_x^2 = e^{2\bar{y} + \sigma_y^2}(e^{\sigma_y^2} - 1) \quad (33)$$

$$\alpha_x = e^{3\bar{y}}[e^{(9/2)\sigma_y^2} - 3e^{(5/2)\sigma_y^2} + 2e^{(3/2)\sigma_y^2}] \quad (34)$$

and

$$C_v = \sigma_x/\bar{x} = (e^{\sigma_y^2} - 1)^{1/2} \quad (35)$$

$$C_s = \alpha_x/\sigma_x^3 = (e^{3\sigma_y^2} - 3e^{\sigma_y^2} + 2)/(e^{\sigma_y^2} - 1)^{3/2} \quad (36)$$

As the best estimate of C_s is obtained by substituting σ_y^2 by s_y^2 (s_y is the y-standard deviation of the sample), the distribution of C_s can be easily obtained correspondingly, and we can test the hypothesis of $C_s = 1$ by the likelihood ratio test. In this case the hypothesis $C_s = 1$ is admissible and we could use Hazen's results. It may be noted that for $e^{\sigma_y^2} = 1$ the computation of Chow is correct, but for $e^{\sigma_y^2} = 1.105$ there are some misprints though the value of C_v is correct.

As the values of C_v and C_s are those given by Chow, the subsequent analysis follows its general way.

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J. Tiago de Oliveira

AUTHOR'S RESPONSE

The author deeply appreciates de Oliveira's interest in the discussion of a general formula for hydrologic frequency analysis. The procedure of transformation employed in the discussion has followed the work of FISHER [1926]. However, it was found later that the procedure for the present problem should be revised as shown in author's Technical Draft [CHOW, 1955]. The resulting equations are therefore in agreement with those presented by de Oliveira. Furthermore, it was discovered that a high percentage of Hazen's approximate results are in error [CHOW, 1954]; and accordingly, a complete set of exact theoretical values of frequency factor were calculated, which are recommended for use in the theoretical treatment of hydrologic data.

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Transactions, American Geophysical Union Volume 36, Number 3 June 1955

DISCUSSION OF

"THE EARTH'S CORE"
by S. K. RUNCORN

[Trans., v. 35, pp. 49-63, 1954]

E. C. Bullard (National Physical Laboratory, Teddington, Middlesex, England, received June 21, 1954)--Runcorn has given a very interesting outline of the dynamics of the Earth's core, much of which should meet with general agreement; parts of the argument are, however, open to serious objection. On page 53, he estimates the orders of magnitude of the terms in the equation of motion for a rotating sphere, and concludes that the buoyancy forces must be balanced by the pressure gradient and Coriolis forces. Since neither Coriolis forces nor the pressure can absorb energy, this is impossible, and, in fact, multiplying Runcorn's (3) by v and integrating through the core leads to a contradiction. If the motion is driven by the buoyancy forces, the energy must be absorbed either by viscous forces or by the magnetic field. From Runcorn's Table 1 this requires either that the eddies be about a kilometer across, or that the magnetic field, and therefore the electric currents, be a hundred times greater than he has assumed. Since small eddies are of little use for theories of geomagnetism, it seems wise to choose the latter alternative and to postulate a toroidal field much greater than the dipole field and than the three gauss assumed by Runcorn. The reasons for supposing such a field to exist have been extensively discussed by Elsasser and by the present writer, and it seems highly probable that any theory of the magneto-hydrodynamics of the core must provide a magnetic field of such a size that the buoyancy forces the electromagnetic forces and Coriolis forces are all of the same order of magnitude.

The argument on page 58 appears inconsistent with that on page 57. A thermoelectric theory of the Earth's magnetic field is said on page 58 to require "temperature differences of some hundreds of degrees......over the core-mantle-interface", whilst on page 57 it is shown that even if only 10^{-4} of the material takes part in the convective motion the temperature difference between the rising and falling currents cannot exceed 0.1°C. It is difficult to see how the temperature differences on the core-mantle boundary can differ in order of magnitude from those within the core; the discrepancy is actually much worse than it appears, since the assumption that only 10^{-4} of the core moves would make it difficult to generate a dipole field from a toroidal field by the process mentioned on page 59. If a thermoelectric theory of the Earth's magnetic field is to be established, it seems necessary to consider these matters in more detail than has yet been attempted.

L. Slaucitajs (Observatorio Astronomico, Eva Peron, Argentina, received June 24, 1954)--In this paper and in following discussion by Vestine and Elsasser are not mentioned all known morphological characteristics of the observed geomagnetic secular variation. Some of characteristics, indicated in 1948, can be useful for the relations analysis between the phenomenon of the secular variation and the core movements. Chronologically these are: SLAUCITAJS [1948] indicated one probable secular variation 'period' of about 50 years; WASSERFALL [1950] mentions an approximate periodic variation in secular change of about 70 years; VESTINE [1952] confirms a pulse of about 60 years duration (cited in the discussion of Symposium, p. 63); and BROUWER [1952] confirms from this astronomical data the fluctuation in the Earth's rotation in a period of 50 years.

Also the fact of the increase of Earth's mean magnetization (after the well-known decrease), indicated by GAIBAR-PUERTAS [1952] (compare with ELSASSER's statements in Symposium discussion, p. 75) should be taken in account in the present-day discussions of the problems of the Earth's core and the geomagnetic secular variation.

S. K. Runcorn (Department of Geodesy and Geophysics, Cambridge University, Cambridge, England, Author's closure)--In the present stage of discussion on the origin of the main geomagnetic field, I believe it is possible to infer only the essential character of the processes in the Earth's interior. Thus in my paper, I pointed out that the dominant role of the Coriolis force on motions in the core was the probable reason for the coincidence of the mean magnetic axis with the geographical one. R. Hide, D. T. Griggs, and G. I. Taylor, in private communications, have pointed out to me that the spherical boundaries of the core cause the motions to be of a more restricted type than the two-dimensional ones that I suggested. Accepting my assumption that it is permissible to omit from the hydrodynamic equation all terms of small magnitude, (3) of my paper becomes

$$2\vec{\omega}\wedge\vec{v} = -\nabla p/\rho + (1 + T\beta)\vec{g}$$

where $\vec{\omega}$ is the Earth's angular velocity about the z axis, $\vec{v}$ the velocity of the motion, p the pressure, ρ the density, g the gravitational force, T the temperature at any point and β is the coefficient of thermal expansion. From this I derived

$$2(\vec{\omega}\,\nabla)\vec{v} = \beta\vec{g}\wedge\nabla T$$

As $\vec{g} = \alpha\vec{r}$ in the core this becomes $2\,\omega\,d\vec{v}/dz = \alpha\beta\vec{r}\wedge\nabla T$

Now at the boundary $\vec{v}$ has no component in a radial direction, thus the velocity cannot anywhere have a radial component and the allowed motions in the core must everywhere be perpendicular to the radius. In addition, if T is constant everywhere, the velocity along a line parallel to the z axis must be constant. Thus the velocity cannot have a component in a meridional plane and purely cylindrical motions about the z axis result. I have experimentally demonstrated this by rotating a sphere full of water in which a small solid sphere containing a magnet was held at the centre by a string. With an external magnet the small sphere was deflected to cause motions, which were shown up in the usual way by the reflection of light from suspended aluminium powder. It was found that the only motion which could be produced in the rotating sphere was the cylindrical motion referred to above and any more complicated motion simply consisted of a large number of small eddies. Thus the attempt to produce a more complicated two dimensional motion gives rise to small eddies in which acceleration and viscous forces become important, in which case the assumptions on which (3) is based break down. A similar discussion of the effect of spherical boundaries for the case of a fluid of uniform density is given by BULLARD and GELLMAN [1954].

Bullard remarks above that the electromagnetic forces should be included in (3). It is clearly true that buoyancy forces due to a possible excess of the actual temperature gradient over the adiabatic gradient in the core are the forces which produce energy. As FRENKEL [1945] showed, a fantastically small excess temperature gradient would cause prohibitively large velocities if the motion was only resisted by the viscosity of the fluid. Consequently it must be the electromagnetic forces which largely balance the buoyancy forces. However in the absence of both these forces, the viscous forces being negligible, motions would persist in the core when once started and it seems reasonable to suppose that the general motion of the fluid within the core can be discussed without reference to the driving and dissipating forces as is usual in the discussion of the general circulation of the atmosphere. Nevertheless, as shown above, this argument leads to a cylindrical motion appropriate as an explanation of the westward drift but trivial in other respects. The general physical argument that the eddies lie parallel to the axis of rotation has not, however, been refuted.

Bullard comments that it is doubtful if temperature differences of the order of hundreds of degrees can exist over the core-mantle interface, only much smaller differences over the adiabatic gradient distribution being allowable within the core. However if the motions having a component parallel to the axis of rotation were inhibited by the rotation of the Earth there would be no reason why considerable differences of temperature between the polar and equatorial regions should not exist. I did not, in my paper, make clear that it is unlikely that the temperature varies appreciably with longitude. Recent consideration of the problem of providing an explanation of reversals of the main geomagnetic field [RUNCORN, 1955a] suggests that it may be helpful to postulate the existence of large toroidal magnetic fields within the Earth's interior which remain substantially constant over long periods of geological time, the reversal of the dipole field arising from comparatively minor changes in the pattern of motions within the core. The generation of such a toroidal field by thermoelectromotive forces between the core and the mantle arising from a rather permanent distribution of temperature is attractive. The quantitative basis of such a suggestion at present remains necessarily vague.

With regard to Slaucitajs' remarks on the secular variation, it is likely that the spectrum of the latter is broadly spread over periods of a few tens of years to some thousands of years. It seems unlikely that a discrete periodicity in the geomagnetic secular change exists. H. Hughes and A. F. Moore, quoted by RUNCORN [1955b], have from a combination of observatory data and palaeomagnetic results determined the rough form of the spectrum.

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DISCUSSION OF

"WAVE RUN-UP ON SLOPING STRUCTURES"
by K. N. GRANTHEM

[Trans., v. 34, pp. 720-724, 1953]

Richard Silvester (University of Western Australia, Nedlands, Australia)--The paper provides useful information on the design of hydraulic structures subject to wave action. Mention was made of surface roughness under the heading 'Experimental Results', 'It is apparent from examination of these waves that there is a great advantage in having structures with high roughness coefficients and with relatively large porosity.' Beyond this there is no reference to the friction encountered by the wave in running up the slope.

One method of comparing porosity with surface roughness would be to have a 'structure' comprised of ripple or corrugated iron, with the corrugations horizontal. After testing the original iron, it could then have holes drilled or punched in it to give any desired degree of porosity, even a variable porosity up the slope. Tests on the perforated iron could then be compared with those on the original iron and also with those on the smooth surface with zero porosity as listed.

It is hoped that the author can do this with the equipment available and that further results can be issued.

DISCUSSION OF

"PRECIPITATION MEASUREMENTS ON WIND-SWEPT SLOPES"
by AUSTIN E. HELMERS

[Trans., v. 35, pp. 471-474, 1954]

John C. Kurtyka (1611 S. Connell St., Appleton, Wis.)--In mountainous regions a need exists for measuring that portion of precipitation entering vertical planes. The standard eight-inch gage theoretically measures the precipitation which falls upon a horizontal surface. Helmers' report indicates that during two periods the stereo gage was effective in accounting for both the effects of horizontal and vertical components of the precipitation when compared to that which reached the mountain slope. The author compares the catch of a shielded stereo gage with that of a shielded standard eight-inch gage and states that the stereo gage with tilted shield is presumed to be the most accurate of the gages tested. Certain exposure characteristics of the two gages will be discussed to show that the geometry of the gages prevents a true comparison.

It was stated that the catch of the stereo gage would be equivalent to that of a tilted gage multiplied by the secant of the angle of slope which in turn expressed the precipitation on a horizontal basis. Use of the conversion equation and treating the catch of the tilted gage instead of the stereo gage will simplify discussion of the comparison.

When the direction of precipitation elements is down slope, due to its elevated position, the horizontal orifice can theoretically catch those elements with a trajectory lying between the angle of slope and the horizontal whereas the tilted gage could not since its orifice is parallel to the slope. Assuming that all the precipitation fell in the foregoing manner the conversion equation would be the inequality: Secant $\theta \times$ zero $\neq$ precipitation caught in horizontal orifice, where θ is the angle of slope.

A similar condition applies to the precipitation elements which move up slope at trajectories lying between the angle of slope and the horizontal. In this case the elements would be able to enter the tilted gage but not the standard horizontal gage. Assuming that all the precipitation was at the foregoing trajectory the conversion equation would be the inequality: Secant $\theta \times$ precipitation caught in stereo gage $\neq 0$.

In order to compare the two types of gages, it is necessary to adjust the catch of the tilted gage for that portion of catch which occurred at trajectories as noted in the foregoing two examples and which for all practical purposes is not possible.

Austin E. Helmers (Intermountain Forest and Range Experiment Station, Ogden, Utah, Author's closure)--Kurtyka correctly states that the catch of a stereo gage is equivalent to that of a tilted orifice multiplied by the secant of the angle of the slope, which in turn expresses the precipitation on a horizontal area basis. Note that in my paper no reference is made to the catch of a horizontal orifice. The catch of a horizontal orifice on a slope is quite a different matter than the amount of precipitation received on the slope over a vertical projection of an equal horizontal area. The conversion equation cannot be applied to the catch of a tilted orifice to obtain the catch of a horizontal orifice. However, on a slope it can properly be applied to the catch of a tilted orifice to determine the catch on a horizontal area that is equal to the vertical projection of stereo or horizontal orifices.

DISCUSSION OF

"HYDRAULIC HEAD LOSS AT THE INTERFACE BETWEEN UNIFORM SANDS OF DIFFERENT SIZES"

by FRANK N. LEATHERWOOD and DEAN F. PETERSON, JR.

[Trans., v. 35, pp. 588-594, 1954]

Mahdi S. Hantush (Research and Development Division New Mexico Institute of Mining and Technology, Socorro, N. M., received Sep. 13, 1954)--The paper under discussion is a definite contribution to the study of filter design and related subjects. The result of the authors' work as given by (4) is restricted, however, to packings of sands in which the grain-size range is relatively narrow. A more general solution in which this restriction is removed can be obtained. This solution depends upon the hydraulic conductivities of the different sands which are either known or can be measured by simple permeability tests.

The interface between two packings of sands is actually a thin bed of sand resulting from the partial entry of the small-sized particles into the pores of the contiguous bed of larger-sized particles. Thus the flow actually is through three consecutive sands of different permeability. This situation is illustrated diagrammatically in Figure 7.

Stated mathematically, the boundary value problem is given by the following system of equations

$$d^2h/dx^2 = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

$$\left.\begin{array}{lll} h_1(o) = h_o & h_1(a) = h_2(a) & K_1\, dh_1(a)/dx = K_2\, dh_2(a)/dx \\ h_2(a+b) = h_3(a+b) & K_2\, dh_2(a+b)/dx = K_3\, dh_3(a+b)/dx & h_3(a+b+c) = o \end{array}\right) \ldots (6)$$

where (5) is the differential equation for unidirectional and viscous flow through porous media, and where, h is the piezometric head at any section of the flow, and where

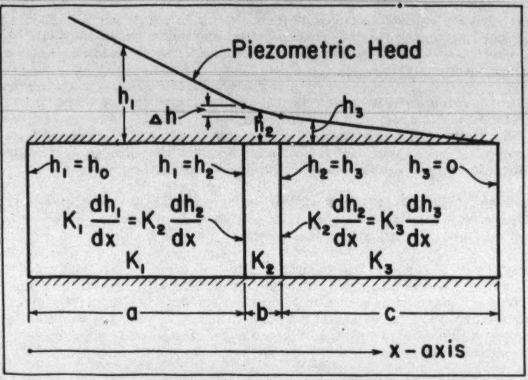

Fig. 7--Diagrammatic sketch of flow conditions

a, b, c	are the lengths of three sand packings of different permeability (see Fig. 7)
K_1, K_2, K_3	are the hydraulic conductivities of the three sands respectively
h_1, h_2, h_3	are the piezometric heads in the three sands respectively
h_o	is the constant head at the intake face

It can be shown that the solution of the above boundary value problem is given by

$$\left.\begin{aligned} h_1 &= h_o\ [1 - K_2 K_3\, x/(a K_2 K_3 + b K_1 K_3 + c K_1 K_2)] \\ h_2 &= h_o\ [K_1 K_2 c + K_1 K_3\, (a + b - x)]/(a K_2 K_3 + b K_1 K_3 + c K_1 K_2) \\ h_3 &= h_o\ K_1 K_2\, (a + b + c - x)/(a K_2 K_3 + b K_1 K_3 + c K_1 K_2) \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots \quad (7)$$

The loss of head due to the movement of water through the intermediate bed is the head lost at the interface of the two sand packings. This is given by

$$\Delta h = h_2\,(a) - h_2\,(a + b) = K_1 K_3\, b h_o/(a K_1 K_2 + b K_1 K_3 + c K_1 K_2) \quad \ldots\ldots \quad (8)$$

The hydraulic conductivity for any sand is given by $K = CD^2\ \gamma/\mu$, where D is the mean diameter of sand grains, γ is the specific weight of the fluid, μ is the dynamic viscosity of the fluid, and C is a factor which depends upon the porosity of the sand, the range and distribution of grain sizes, the shape of the grains, and their orientation and arrangement, all of which are characterized by dimensionless length ratios or angles. Obviously, then, the effect of the parameters involved in the functional relationship in (1) of the paper under discussion are included in the description of the hydraulic conductivities of the three different sands.

In developing (8), no restriction is imposed on the range of the grain size of the different sands. Thus this equation is applicable in viscous flow through sands whose hydraulic conductivities are known.

The hydraulic conductivity of any sand can be measured in the laboratory. Of all the parameters of (8), K_3 and b may be difficult to estimate. These parameters depend upon the degree and extent of mixing between the grains of the two different sands at the interface. It is to be noted, however, that the error introduced by inaccuracies in measuring K_3 and b may be of the same order, if not less than that introduced by estimating the parameters of (4). It would be interesting to check the validity of this general equation by data from the experiments on which the authors based their analysis.

Carl Rohwer (Agricultural Research Service, retired, Colorado A + M College, Ft. Collins, Colorado, received Dec. 9, 1954)--The loss of head at the interface between sand and gravel is of importance in the study of gravel envelopes for the control of sand pumping in wells. Although this head loss may not be a significant factor in most cases, the changes in the losses that occur as the sand moves into the gravel envelope at the interface may be important.

Tests made by LOCKMAN [1954], show that the total head loss through the gravel pack is unaffected initially by the movement of small quantities of sand into the gravel. However, if the sand movement continues, it will ultimately increase the head loss.

In his study it was also shown that the uniformity coefficient of the sand and of the gravel, had a definite effect on the filtering action of the gravel. A similar effect on the head loss at the interface, was noted by the authors, as shown in Figure 5. The data in the figure indicate that σ, a measure of the uniformity of the sand and the gravel, has more effect on the head loss than the ratio of the sizes. The points do not all fall on the curve, but this is not surprising in view of the difficulty in compacting the samples to exactly the same degree for each test.

The concave curves in Figure 6, for uniform materials where the ratio of sizes D_1/D_s is greater than 5, indicate that the head loss at the interface decreases as the velocity increases after reaching a maximum. Lockman's tests showed that the total head loss in the gravel increased as the velocity increased if the ratio of sizes exceeded 7. Lockman attributed the increase in head loss to the clogging of the gravel with sand, which seems reasonable. However, the head loss at the interface may actually have decreased due to the washing out of fine particles as suggested by the authors.

The head losses, whether measured at the interface between the sand and gravel or as the total loss through the gravel, are not static quantities; those losses change with time and the only way to get comparable results is to make the observations systematically after definite and uniform time intervals. Apparent differences in the results by different observers may well be due to this cause alone, although differences in method of compaction of the materials may be equally effective in causing discrepancies in the results.

Frank N. Leatherwood and Dean F. Peterson, Jr. (Colorado Agricultural and Mechanical College, Ft. Collins, Colorado, Authors' closure)--Hantush objects to the solution of the authors' on the grounds that it is restricted to sands of narrow size range. Using boundary-value methods, he restates the solution to the problem of flow through three permeable beds in series and proposes this as a generalized solution to the authors' problem. The solution to the series flow problem is well known and may be deduced much more readily and simply by application of Darcy's equation [TERZAGHI, 1943, Art. 89]. Given n permeable beds in series flow having the thicknesses $b_1, b_2, \ldots b_n$; the permeabilities $K_1, K_2 \ldots K_n$ and associated head losses $h_1, h_2 \ldots h_n$; for a unit discharge q, one may write

$$q = K_1 h_1/b_1 = K_2 h_2/b_2 = \ldots K_n h_n/b_n \qquad (9)$$

$$h_o = h_1 + h_2 + \ldots h_n = q\,(b_1/K_1 + b_2/K_2 + \ldots b_n/K_n) \qquad (10)$$

Solving (9) and (10) for any value of h_i gives

$$h_i = h_o/(b_1 Ki/b_i K_1 + b_2 K_i/b_i K_2 + \ldots 1 - \ldots b_n K_i/b_i K_n) \qquad (11)$$

In (11), the ith term in the denominator is equal to unity. Solving (11) for n = 3, and i = 2 leads to (8).

Hantush evidently missed the point of the author's study, which was to describe the flow across the interface in terms of the basic characteristics affecting it. In lieu of this, Hantush proposes that it simply be estimated. He further states that, once estimated, it can be substituted in (8). This is true, but beside the point.

Quite obviously the clogging in the region of the interface depends on the characteristics of the two original materials and on the flow. The authors chose to describe the clogging in terms of the hydraulic head loss as the dependent variable. A number of combinations of characteristics of the two materials were tried as independent variables and the pertinent ones seemed to be those used in (4) Other independent parameters could have been substituted; for instance, the permeabilities of the large and small size gravels, K_L and K_S, were tried in place of the appropriate d_L, d_S, $\sigma l/D_l$ and $\sigma s/D_S$ values. These did not correlate as well as the parameters used. This seems to indicate that the effect of grain size distribution on clogging phenomena is different from its effect on permeability.

Hantush is incorrect in stating that (8) is a substitute for (3) and (4). He proposes that the clogging phenomenon be characterized by an equivalent bed width and permeability to be estimated by a means which he does not reveal. Actually it is this estimate which is the substitute for (3) and (4) and not (8).

Rohwer's discussion points out the extreme importance of the effect of grain size distribution on the interface phenomenon and notes that this changes with time. The authors believe that if a stable filter is developed, the change with time should eventually become quite small.

References

LOCKMAN, JOHN RICHARD, Selection of gravel pack for wells in fine, uniform unconsolidated aquifers, master's thesis, Dept. of Civil Eng., Colorado A and M Coll., 1954.

TERZAGHI, K., Theoretical soil mechanics, John Wiley, Art. 89., 1943.

REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

PETTERSON, HANS, The Ocean Floor, Yale University Press, New Haven, Conn., 181 pp., 1954, $3.00.

This extremely interesting and very informative book is difficult to review adequately. The reviewer should be a combination of physical and biological oceanographer, stratigrapher, expert on natural radioactivity, and well versed in the history of science. No one but the author combines these attributes, and the present reviewer qualifies only mildly in one of them. The volume concerns itself with all phases of current and past investigations of the ocean bottom and sub-bottom, and of the deeper waters. Quite naturally, the author gives most attention to the results of the recent cruises of the *Albatross* under his direction, and of the *Galathea*, which used much of his equipment and methods; but the work, results, and theories of other expeditions or individuals are given adequately full treatment. The studies of Forbes, the *Challenger*, the *Meteor*, of Piggot and Urry, of the Woods Hole, Columbia, and Scripps teams receive critical attention.

There are here brought together not only past and present work, but also a reasoned account of what is not yet fully worked out, what is imperfectly known, what is unknown, and especially what needs to be done next, with excellent suggestions as to how to do it.

So far as the reviewer can tell, there is only one obvious error. On page 99 it is stated that submarine weathering has in one case altered plagioclase to orthoclase by substituting sodium for potassium. The reverse is stated on page 134. In some respects the book suffers from repetition of the same material in different chapters. This is probably because it was prepared from the notes of the author for the Silliman Lectures of 1952 at Yale. The small format makes the details of some illustrations difficult to make out. These are very minor imperfections in a book which can be read with profit by every oceanographer, geophysicist (*sensu strictu*), geochemist, and geologist, both at the professional and student levels. The scientific amateur, especially if nautically inclined, will find it understandable, interesting, and well written. It should be in all public libraries as well as in all those of colleges and universities.

JOHN PUTNAM MARBLE

ELLIS, CECIL B., Fresh Water from the Ocean, Ronald Press Co., New York, 217 pp., 41 illustrations, 9 tables, 1954, $5.00.

The Conservation Foundation has sponsored publication of this text, the first of its kind on the subject. In the words of the author it is the first systematic examination of the techniques by which salt can be separated from water. In the initial stages of research in this field it was desirable to have summarized in one publication a brief evaluation of the technical merit of all the demineralization techniques thus far proposed including the obviously promising as well as the impractical and unworkable methods. This text fulfills in a large part the need for such an evaluation. Publication of the text is made further appropriate at this time because of the widespread current interest in demineralization. It should serve to answer many questions as well as to correct certain misconceptions about methods of desalting which may have arisen during this initial period of interest in the subject. Current research work on salt-water conversion does not tend to outdate the book, or materially affect its value as a reference source since the text treats primarily the basic and fundamental aspects of the problem. Bibliographies are supplied with each chapter and along with the data given indicate that thorough technical preparation has been made for the publication. The author has been remarkably successful in making a scientific subject readable. The text can be understood by anyone having a general technical background. However, scientific accuracy and the usefulness of the text for technical purposes has not been sacrificed in favor of popular presentation. The only criticism made is that the author could advantageously have given a more extensive treatment of solvent extraction as a method of salt removal and similarly could have discussed in more detail the use of atomic energy in providing power for saline water conversion. Likewise, since the author states that he hopes his text will stimulate further research in this field considerable encouragement could have been given the prospective researcher as well as the general reader if the progress achieved toward this goal during the last two decades had been made the subject of a brief section of the text.

The over-all technical objective is to appraise the current status of each phenomena of salt separation and to evaluate from a theoretical standpoint the promise of further development of the various phenomena for the purpose of extracting fresh water from the ocean in large quantities at low cost. The author has recognized that cost is the all important criterion for determining the practical use of salt water conversion methods. Cost calculations are incorporated with the technical review of energy and material relationships throughout. For comparative purposes costs for the various methods are based on a projected plant capacity of 1,000 million gallons per day or as much water as would be used daily by New York City. The author has employed a very effective procedure both for evaluating the methods for salt removal and for stimulating critical thinking about possible ways of removing the salt. A method of salt removal is presented followed by reasons why the method is or is not technically feasible. Assuming technical feasibility, an estimate is then made of potential production cost. The author has made a very comprehensive coverage of all the phenomena to be applied to salt separation. Although the detail given is limited in the case of the less attractive methods, it appears that none have been overlooked. The author stresses the importance of ingenuity in further improving methods of salt removal. The author himself should be commended for the ingenuity he has presented in setting up salt removal methods, both the workable and unworkable arrangements. Among the basic phenomena of salt separation discussed are: evaporation, dialysis, electrolysis, osmosis, ultrasonics, freezing, diffusion, adsorption, centrifuging, precipitation, and ion exchange. In addition, discussion is devoted to energy sources and their application, sale of by-product chemicals, and a brief reference to ideas for bypassing the problem, such as towing icebergs and the use of salt water without the removal of the salt. A separate chapter is devoted to sample design criteria and cost calculations for a 1,000 mgd membrane plant. The author concludes that the electric membrane method is expected to be the cheapest method to date with vapor compression distillation rated as second cheapest.

The text is of chief value as a reference on basic technical facts on various salt removal techniques and as a summary of estimated costs for these methods. It does not present detailed description of actual operating plants. It cannot, therefore, be used as an engineering reference to obtain design data and operating characteristics of equipment being manufactured.

E. H. SIEVEKA

TARDI, PIERRE, and GEORGES LACLAVÈRE, Traité de Géodésie, Volume I, Book 2: Calcul de la Triangulation, Gauthier-Villars, Paris, x + 334 pp., 1954 (Book 1 on Mathematical Foundations of Geodesy and Field Operations was reviewed in v. 33, p. 129, 1952).

This completes the first volume of the revised and enlarged edition of Tardi's Traité de Géodésie. The material covered in this volume parallels that of the first book of the 1934 edition and the expansion of this work to almost twice its former length results in a clear, complete, and consecutive treatment of all the practical aspects of triangulation computation and adjustment on an ellipsoid subject to the restriction that the normal to this surface coincides with the vertical. Complications introduced by deflections of the vertical are to be treated in Volume III after the introduction of the problems of physical geodesy.

The first chapter of this second part, Chapter VII, deals fully with the geometry of geodesics, on the ellipsoid of revolution, and ellipsoidal triangles. This leads to a chapter on forward and inverse computation of coordinates with a variety of solutions, each limited in scope by considerations of accuracy, length of line, available tabulation, etc.

Chapter IX is a well-organized development of the application of plane coordinates to triangulation computations. Through a judicious selection of topics, omitting what is of purely historical or cartographic interest, the authors succeed in compressing into a hundred pages all aspects of importance to the practicing geodesist on the subject of conformal projections. The included discussion of the Madagascar projection, which is in the nature of an introduction to Laborde's work, is a welcome addition to the geodetic literature.

The last chapter is devoted to the subject of triangulation adjustment proper. Here again the emphasis is on modern practice which parallels rather closely the concepts and methods used in this country. Adjustment by variation of plane and geodetic coordinates, which in recent years has replaced to a great extend the less flexible adjustment by condition equations, is treated first, followed by sections on the direction method and the Levallois method of bearings (gisements). The volume is concluded with a collection of miscellaneous surveying topics arising in connection with lower order nets and traverses.

Comprehensive and up-to-date expositions on this subject are a rarity and this treatise shows promise of becoming a standard reference for some time to come. Certainly it deserves a place in every geodetic library.

ERWIN SCHMID

DAVIS, WILLIAM MORRIS, Geographical Essays (Douglas Wilson Johnson, Ed.), Dover Publications, New York, vi + 777 pp., 130 figures, 1954, $5.50.

This is an unabridged republication of the 1909 edition of this classic work.

Abstracts of the papers presented at the Thirth-Sixth Annual Meeting, Washington, D. C., May 2-4, 1955 listed in the order of the last name of the first author

William Mansfield Adams (Institute of Technology, St. Louis University, St. Louis, Mo.) The Reeff Horizontal Seismograph and its Calibration--A new horizontal seismograph, having high magnification and excellent initiation of phases, has recently been invented by Nicholas Reeff. The instrument consists of an inverted pendulum seismometer, an electrodynamical generating system, and galvanometric registration. Since the pendulum mass is less than seven kilograms, galvanometric reaction on the seismometer motion must be considered in the calibration procedure. For calibration, the first adjustment suggested by Eaton (Theory of the Electromagnetic Seismograph, Bull. Seis. Soc. America, in press; an extension of the theory along lines suggested by Coulomb and Grenet) was applied. For the periods of the seismometer and galvanometer both equal to 1.92 sec, the damping of the galvanometer equal to 1.00, and the damping of the seismometer equal to 1.70, the peak magnification was determined to be 5550 at a period of 5.3 sec.

Maurice L. Albertson (Civil Engineering Department, Colorado A and M College, Fort Collins, Colo.) Evaporation from a Free Water Surface--A program of laboratory investigation under controlled conditions in the wind tunnel was initiated to study certain fundamental principles of evaporation (vapor transfer), including its relation to heat transfer and the boundary layer (momentum transfer). Evaporation may take place under condition of free convection or forced convection, and the heat of vaporization may be supplied by conduction through the sides or bottom of the liquid container, by radiation to the surface of the liquid, by the air moving across the surface (forced convection), or by a combination of these. Although each of the methods is important, the only one studied in this investigation is the forced convection--heat transfer by each of the other methods being held at zero as nearly as possible. Because evaporation is vapor transfer in an 'evaporation layer' similar to heat transfer in a 'heat layer' and momentum transfer in a dynamic boundary layer, it is logical that previous work should be applicable to evaporation. It was found that evaporation could be expressed in a function involving an evaporation parameter N similar to the Nusselt number, a special form of the Reynolds number R, a shape factor sf, and a roughness parameter k/L, thus $N = \phi_1$ (R, sf, k/L), where $N = Ex/\Delta C \nu_e$, $R = U_* x/\nu_e$, U_* is the shear velocity at the downstream end of the evaporation surface, x is the distance downstream from the beginning of the evaporation boundary, ν_e is the molecular diffusivity coefficient for water vapor into air, E is the evaporation weight per unit area and unit time, ΔC is the difference between the saturation vapor concentration at surface temperature and the vapor concentration of ambient air, k is boundary roughness, L is characteristic length dimension of evaporation surface. The data which have been taken in both the laboratory and the field support the validity of this relationship. The flow may be either laminar or turbulent and the lapse rate may be neutral or causing either an inversion or a lapse. The different effect of each factor is reflected in the boundary shear τ_0. Finally, for the conditions studied, the influence of the shape factor sf and the surface roughness parameter k/L was found to be of secondary importance so that $N = \phi_2(R)$ as a first approximation.

L. T. Aldrich, G. L. Davis, G. R. Tilton, and G. W. Wetherill (Department of Terrestrial Magnetism and Geophysical Laboratory, Carnegie Institution of Washington, Washington, D. C.) Comparative Radioactive Age Measurements of Igneous Rocks near Gunnison, Colorado--Age measurements obtained by applying the decay schemes of U, Th, Rb and K have been completed on granitic and pegmatitic minerals from the Quartz Creek area east of Gunnison, Colorado. The apparent Rb-Sr and K-A ages of biotite and feldspar in the granite and lepidolites and feldspars in the pegmatite and the apparent U-Pb and Th-Pb ages of zircon in the granite and monazite in the pegmatite have been determined. The results show the difficulties in applying each of the four decay schemes to such systems of minerals. It now seems for these types of mineral associations that the Rb-Sr ages are most reproducible and that the K-A method applied to micas gives results consistent with but 13 per cent lower than those from the Rb decay. This study demonstrates the necessity of multiple measurements on any igneous body whose age is to be determined. The results obtained are most compatible with an age of 1500 ± 100 m y for the Quartz Creek area.

William W. Anderson (U. S. Fish and Wildlife Service, Washington, D. C.) and Robert B. Abel (U. S. Navy Hydrographic Office, Washington, D. C.) Expeditions of the M/V Theodore N. Gill off the South Atlantic Coast of the U. S., 1952-1954--The U. S. Navy Hydrographic Office, the Fish and Wildlife Service, and Office of Naval Research are jointly prosecuting a program of the oceanography of the offshore waters from Hatteras to Straits of Florida. A two-year program of bimonthly cruises has recently terminated. Measurements of physical and biological properties, chemical content, and meteorological conditions were carried out.

H. Arakawa (Meteorological Research Institute, Tokyo, Japan) Japanese Forecasting of Changes in Sea Level Induced by Typhoons--In Japan, the problem of induced changes in sea level by typhoons is one of the largest community problems, because these abnormal storm tides ('Takashio' in Japanese) often cause very severe property damage. Usually the sea level under the influence of typhoons can be satisfactorily predicted by adding the effects of three important variables, namely, fetch and duration of the surface wind, and the predicted astronomical level. Moreover, dynamic effects, especially the natural frequency of the bay and the speed of advance of the typhoon, sometimes play important roles. Some historical storm tides in Japan are given as illustrations.

Bernard F. Armbrust, Jr. and P. K. Kuroda (Department of Chemistry, University of Arkansas, Fayetteville, Ark.) On the Isotopic Constitution of Radium (Ra-224/Ra-226 and Ra-228/Ra-226) in Petroleum Brines--The Ra-224, Ra-226, Ra-228 contents of a number of petroleum brines from Oklahoma and Arkansas have been determined. The radium isotopes were precipitated with barium sulfate from brines (500 ml to ten liters), and the beta-radioactivity was measured with an end-window Geiger counter. Out of about ten samples studied, about the half gave growth-curves due to the thorium series radium isotopes (Ra-224 and Ra-226) and the rest gave growth-curves of the mixture of the thorium series and the uranium series radium isotopes. The relative amounts of Ra-224, Ra-226 and Ra-228 were calculated from the growth-curves. The highest concentration found was more than 10^{-9} curies per liter of brine.

George B. Austin (Department of Oceanography, A and M College of Texas, College Station, Texas) Recent Oceanographic Cruises in the Gulf of Mexico--A discussion of five recent oceanographic Gulf of Mexico cruises is presented with emphasis on the planning and results of Cruise 54-10 of the A. A. Jakkula, which was taken in August-September of 1954. An apparently semi-permanent, large scale, anti-cyclonic eddy which was repeatedly observed on four earlier oceanographic surveys was investigated in greater detail during the past summer. Evidence from the five surveys made in the region of the eddy indicates that the eddy is an integral part of the Gulf Stream system in the Gulf of Mexico. It is somewhat similar in size and behavior to large scale cyclonic eddies described by Fuglister (WHOI) for the Gulf Stream in the Newfoundland Banks area. The major differences are the permanent or semi-permanent aspects of the large scale Gulf of Mexico eddy and its intense anti-cyclonic direction of rotation. From the single ship survey of Cruise 54-10 an attempt was made (1) to locate and define the eddy, (2) to establish whether or not it was a temporary or permanent feature of the Gulf of Mexico and the Yucatan Current and to determine whether or not it changed physically in space and time, or both.

Henri Bader (Snow, Ice, and Permafrost Research Establishment, Wilmette, Ill.) Research on the Physical Properties of Ice--No abstract available.

Clifford A. Barnes (Department of Oceanography, University of Washington, Seattle 5, Wash.) Oceanographic Expeditions of the Brown Bear in the Northeast Pacific--Through the Office of Naval Research the Brown Bear was made available to the University of Washington in June, 1951. The vessel has been readied for oceanographic work and an active field program has been carried out. Offshore studies have stressed the characteristics and circulation of the coastal waters to 300 miles seaward from Oregon to Vancouver Island, and the Gulf of Alaska from the Queen Charlotte Islands to Kodiak Island. Various methods of determining currents show a weak oceanic circulation off the Washington Coast which is partly obscured by relatively strong and variable transient currents. The outflow of the Columbia River has been traced for 200 miles southwest of the river's mouth. On the Gulf of Alaska cruise in 1954 conventional physical and chemical measurements were made at 60 stations with depths of observation ranging to 5000 meters. The existence of a counterclockwise surface circulation was confirmed. Plankton samples were collected at each station and showed relatively high zooplankton concentrations. Core samples were collected from representative locations of which some contained gravels and sands, and others, strata of volcanic ash and foraminifera ooze.

George L. Bate and J. Laurence Kulp (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) Variations in the Isotopic Composition of Common Lead and the History of the Earth's Crust--Isotopic analyses of over 150 common lead samples have been completed in a reconnaissance of lead minerals from all of the continents, including a suite of pre-Cambrian leads from Southern Africa. Least squares analysis of a number of dated samples gives constants which agree well with those previously obtained by the same method. If the isotopic composition of meteoritic lead obtained by Patterson is taken as the primeval lead composition, an age of the Earth's crust is obtained which is considerably larger than that calculated without meteoritic lead data. This discrepancy has led to formulation of a model which permits differentiation of the Earth's crust throughout geologic time in an exponential manner. The constants introduced are evaluated independently of lead ore data and these calculations show that the maximum age of the Earth is approximately 5.3 billion years, i.e., the time when terrestrial lead had the composition of meteoritic lead. It is further shown that the major portion of the differentiating forces was expended in a time somewhat in excess of a billion years, leading to an apparent age of the Earth's crust of the order of four billion years.

W. Boynton Beckwith (United Airlines, Denver, Colo.) Hail Observations in the Denver Area--Six years of hail data (1949-1954) have been collected and studied to establish patterns of frequency, size, distribution, and time of occurrence. The source of these data is an unofficial network of approximately 40 hail reporting stations concentrated within an area of 100 sq mi centered at Denver. The relationship between point and areal frequencies of several factors has been studied. Upper-air circulation and radiosonde data are investigated on hail and non-hail days to determine additional forecasting aids. Hail observations keyed to characteristic radar echoes are included to indicate the possibilities of this newest observation tool.

John C. Bellamy (Cook Research Laboratories, Chicago, Ill.) Meteorological Observational Requirements for Flight Planning--The formation of flight plans with which aircraft can be utilized most effectively requires accurate forecasts of four dimensional distributions of, primarily, winds and temperatures. Practical methods of presenting such forecasts to flight planners is in terms of charts of horizontal distributions of a stream-function (D values) and its vertical and temporal rates of change. The required accuracy and scope of forecasts generate a requirement for more accurate, more appropriate and more copious observations of such upper-air conditions. Of special importance are observations which provide for accurate evaluations of various kinds of horizontal gradients. A convenient and practical way of obtaining the required observations is to utilize the observational capability characteristic of any and all transport aircraft which are to be operated most effectively.

Willard H. Bennett (Naval Research Laboratory, Washington 25, D. C.) The Störmertron (discussion and demonstration)--A laboratory tube has been developed in which the shapes of the orbits of charged particles in the Earth's magnetic field can be shown to scale and will be demonstrated. The present tube does not duplicate orbit shapes for protons with as small energy as anticipated in the solar proton stream theory of the aurora (1-5 Mev), but some of the consequences of that theory can be shown qualitatively. These include: (1) the restriction of particles from the Sun to particular aurora zones of magnetic latitude; (2) the magnetic concentration of incoming particles with associated intense local magnetic disturbances; (3) the magnetic dispersal of a narrow beam of particles into a complicated system of orbits occupying a volume generated by rotating a crescent about the magnetic axis of the Earth with the horns of the crescent touching the Earth at the auroral zones, thus producing a ring-current. A new tube will be described which is being built and which can produce accurate scale models of orbital forms for all proton energies above 1 Mev, for all impact parameters and for all directions of approach.

William E. Bonini and George P. Woollard (University of Wisconsin, Madison, Wis.) A Comparison of Two High-Range Geodetic-Type Gravimeters--The 1954 world-wide gravimeter program of the Office of Naval Research and Woods Hole Oceanographic Institute included visits to 38 countries with two high-range geodetic-type Worden Gravimeters. The survey resulted in establishment of a well-controlled network of primary gravimeter stations on a leap-frog circuit around the Earth with loops of short time duration to most of the European fundamental stations. In addition, closed loops were made to occupy Cambridge pendulum sites in South Africa, Australia, and New Zealand.

A comparison of the two instruments is made of: (1) drift characteristics and loop closures, and (2) gravity intervals over a range of 5000 mgal. Not considering the accuracy of the instrumental calibration on an absolute basis, the comparison of results indicates the relative accuracy of observed values to be on the order of 0.5 mgal.

Iris Y. Borg and John C. Maxwell (Department of Geology, Princeton University, Princeton, N. J.) Interpretation of Fabrics of Experimentally Deformed Sands--Quartz sands deformed at 26,000-32,000 psi, 270-320°C for periods of 24 hr to 100 days in the presence of alkaline solutions experience a reduction in porosity and permeability and are markedly coherent. Slight reduction in size of grains, interlocking grain boundaries and extensive fracturing are conspicuous features. $r(10\bar{1}1)$ and $z(01\bar{1}1)$ are the most important surfaces of rupture and make up 44 pct of all fractures; planes in the prism zone, particularly $m(10\bar{1}0)$, make up 19 pct of the remaining breaks. Fractures occupy a cone 15° from the axis of compression and are interpreted as tension fractures. Grains of the deformed sand are dominantly elongated parallel to the c axis and r and z. A strong dimensional orientation of grains was produced, and a weak preferred orientation of c axes is a concomitant feature. Petrofabric diagrams are similar to those of natural bedded sandstones.

Lewis M. Branscomb and Stephen J. Smith (National Bureau of Standards, Washington, D. C.) Atomic Oxygen Negative Ion Affinity and Photodetachment Cross Section--The equilibrium electron density in the E region of the ionosphere may be strongly influenced by the loss of electrons by radiative attachment, forming negative ions, and, at dawn and twilight, by the photodetachment of their electrons. The degree of this influence depends on the affinity and photodetachment cross section (from which the radiative attachment cross section may be calculated). The affinity and detachment cross section have been determined approximately in a crossed beam experiment. The O^- affinity is 1.45 ± 0.15 ev, with the possible exception that a sharp resonance at threshold would permit an absolute upper limit of 1.75 ev. The photodetachment cross section apparently rises from this threshold (8550 A) to a value of about 9×10^{-18} cm^2 at 5000 A. This value of the affinity is inconsistent with more indirect previous measurements.

Max C. Brewer (U. S. Geological Survey, Menlo Park, Calif.) Geothermal Investigations of Permafrost in Northern Alaska--Frequent, regular thermal measurements to determine the depth of permafrost and the depth and magnitude of seasonal temperature fluctuation, and to study the effects of topography and engineering structures on the underlying permafrost temperatures have been made in northern Alaska for the last six years. The maximum depth of permafrost noted is approximately 1330 feet. The minimum permafrost temperature recorded, below the depth of seasonal temperature fluctuation (70 to 100 ft), is -10.6°C. Lakes deeper than about seven feet do not freeze to the bottom and may have an unfrozen zone approaching several hundred feet in depth beneath them. It is doubtful if frozen ground within the first hundred feet of depth extends outward more than a few tens of feet from the edge of the Arctic Ocean although frozen ground may be present at greater depths. The temperature effect of medium-sized (40 x 100 ft) heated buildings resting on permafrost ground extends to depths well below 50 ft. Thermal conductivities of frozen surficial materials may vary by a factor of approximately 25.

Max C. Brewer (U. S. Geological Survey, Menlo Park, Calif.) Preliminary Interpretations of Ice, Water, and Bottom Temperature Data in the Arctic Ocean near Barrow, Alaska--Thermal measurements within the ice and in the underlying water have been made in the Arctic Ocean near Barrow, Alaska, during the past four winters. Thermal measurements were also made to a depth of 310 ft beneath the ocean bottom in the spring of 1953. Preliminary interpretation of these data indicates that the water temperatures beneath the ice near shore do not vary by more than 0.2°C during the winter. There is no apparent measureable correlation between the ice temperatures and the salinity of sea ice in place. The data indicate that if the sediments beneath the ocean contain fresh water at a distance of approximately 400 ft off shore, they should be frozen; if the formations contain sea water, they should not be frozen to the depth studied even though they would be classed as permafrost by definition.

Wallace S. Broecker and J. L. Kulp (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) Lamont Radiocarbon Investigations--The development of an improved method for the measurement of C^{14} has been completed. The method consists of measuring CO_2 in large volume proportional counters. Precision of one-half per cent can be obtained on contemporary samples and ages can be determined back to 40,000 years. A study of ocean water samples obtained by the Lamont oceanography group begun several years ago is being continued. Some additional results of the C^{14} concentration of ocean water carbonate as a function of both depth and location in the North Atlantic will be reported. Preliminary data from the new method help define the relationship between the C^{14} content of surface ocean carbonate, the carbon dioxide of the air and the carbon in the biosphere. New results on the application of C^{14} dating in soil-profile studies and archaeology will be presented.

Fred M. Bullard (University of Texas, Austin, Texas) Volcanic Activity in Costa Rica and Nicaragua in 1954--The activity in Costa Rica was limited chiefly to Irazú and Poás Volcanoes, although fumarolic activity was reported at Rincon de la Vieja. The activity of Irazú is entirely fumarolic and of about the same intensity as in previous years. Volcano Poás, which had maintained a geyser-like activity from a lake which filled the bottom of the active crater for many years, began a new eruption in March or April, 1953. This, which appears to be a major eruption, is continuing with a large gas column frequently visible from San Jose and some fresh ash, cinders, and scoria on the upper slopes of the active cone.

The activity in Nicaragua was limited to the following vents: Concepción has been in a mild state of activity since 1948; the explosions, which send out a cloud of gas, occur at intervals of about 30 minutes. Santiago, which has been in a vigorous state of fumarolic activity since 1947, is continuing with some increase in the volume of gas and a corresponding increase in the area in which vegetation is being damaged. Momotombo exhibited fumarolic activity at the summit crater in about the same intensity as in previous years. Las Pilas began fumarolic activity in October, 1952, which has increased steadily in volume; the activity is localized along a fracture near the summit. Cerro Negro contains some active fumaroles in the summit crater. Telica has vigorous fumarolic activity in the summit crater in about the same intensity as in previous years. El Viejo is reported to have some fumaroles in the crater but none were observed in a flight over it in a small plane.

Robert C. Bundgaard (USAF Air Weather Service, MacDill AFB, Fla.) The Required Accuracy of Weather Observations in Jet Aircraft Operations--The type and accuracy of the weather observations required for various phases of jet aircraft operation will be discussed: pre-flighting, take-off, climb-out, cruise, refueling, jet penetration, landing, and on-the-line weather. For illustrating these weather observational requirements, a color film showing a typical weather episode of a B-47 mission will be presented.

Robert C. Bundgaard and Keith Veigas (Air Weather Service, MacDill AFB, Fla.) Synoptic Observations around 40,000 Feet--The accuracies of some of the various direct, quantitative observations near their upper limit in the atmosphere will be discussed: pressure-height, temperature, and wind. Special attention will be directed to the qualitative and visual observations that are being obtained at this elevation from B-47 Weather reconnaissance. The use of these visuals in weather map analysis will then be illustrated.

Eugene Callaghan and Ming-Shan Sun (New Mexico Bureau of Mines and Mineral Resources, Socorro, N. M.) Correlation of Igneous Rocks of New Mexico by Fusion Method--Thirty-six samples of igneous rocks and ten of metamorphic rocks, for which complete chemical analyses have been obtained, were powdered and fused into artificial glasses in the carbon arc of a spectrograph. Curves showing the relation between the refractive indices of such glasses and the composition of the rock samples may be used to estimate the approximate composition and may aid in the correlation of igneous rocks. By this method, the SiO_2-content of an unknown rock sample may be estimated to within 3 per cent of accuracy, whereas MgO, CaO, and the combined Fe_2O_3 and FeO may be estimated to within two per cent of accuracy. The method is not so satisfactorily applied to rhyolite and quartz latite, because these rocks do not readily form homogenous glasses in the carbon arc. Aside from the effect of changing proportions of SiO_2, the refractive indices of the artificial glasses are determined, in decreasing order, by the oxides Fe_2O_3, FeO, MgO, CaO, K_2O, and Na_2O. From comparative studies of variation diagrams, it can be shown why the method is particularly effective for volcanic rocks of intermediate composition, but may not be applied satisfactorily to altered or metamorphic rocks.

W. M. Cameron (University of British Columbia, Vancouver, B. C., Canada) Joint Canadian-United States Beaufort Sea Expeditions--Five consecutive scientific expeditions into the Beaufort Sea and adjoining areas by United States and Canadian vessels were made during the summers from 1950-1954. Their purpose was to describe the bathymetry and oceanography of the area and to make such subsidiary observations which would improve the general knowledge of the region. The scientific personnel represented fourteen government departments and educational institutions in the two countries. The cooperative effort provided an exploratory hydrographic survey of approximately 200,000 sq mi and over 600 oceanographic stations were occupied.

Luis R. A. Capurro (Oceanographic Section, Argentine Navy, Buenos Aires, Argentina) Recent Oceanographic Expeditions in Argentina--A comprehensive program of systematic observations was set up in 1954 on account of the interest that many institutions have in the waters over the extensive continental shelf and continental slope in the Argentine Republic. The Navy undertook the physical observations, while chemical and biological studies were conducted by the Museo de Ciencias Naturales 'Bernardino Rivadavia,' the Fisheries Research Division of the Agriculture

Department, and other private scientists. The Navy oceanographic vessel Madryn made four cruises during the year in the region of the important hake fishing grounds off the province of Buenos Aires. A total of 80 stations were occupied to a maximum depth of 800 m. Results are now being processed and the work will be continued. In the Antarctic, the Navy for the past four seasons has also made systematic observations in the Mar de la Flota (Bransfield Strait) and Drake Passage, between November and March. The new icebreaker General San Martin made a deep penetration into the Weddell Sea in December, 1954, and January, 1955, conducting oceanographic observations on a not-to-interfere basis with her primary mission of setting up a new base on the Weddell Barrier.

Dean S. Carder (U. S. Coast and Geodetic Survey, Washington 25, D. C.) Earthquake Recording in a Deep Mine--Sensitive seismographs were operated by a U. S. Coast and Geodetic Survey field party on the 5000-ft and 300-ft levels of the Homestake mine, Lead, South Dakota, for the purpose of appraising the advantage of a deep mine as a site for earthquake recording. It was found that the 300-ft level was disturbed by a troublesome background noise having periods of one second or less--undoubtedly, originating from mine machinery. The 5000-ft level was relatively free from this disturbance. Four-second microseisms were recorded equally at both stations. Ground amplitudes of emerging P-waves appeared to be somewhat greater near the surface than at depth, although the signal to noise ratio, because of the lesser background, was greater at the deeper station.

Palmer W. Carlin (University of Colorado, Boulder, Colo.) A Computer for Microseismic Azimuths--An electronic apparatus was constructed to do the usual routine azimuth calculations on the records from a tripartite network. This apparatus is fed directly the electrical output of the three micro-seismographs of the network, and immediately records photographically in modified polar coordinates the apparent velocity and direction of approach for each positive crossing of the time axis by the traces. Provision is made to select for calculation only waves greater than a preassigned amplitude. Sample measurements are given.

Howard M. Caulk (Naval Research Laboratory, Washington 25, D. C.) An Electron Beam Magnetometer--A mass-produced miniature tube, National Union type R2211, is here being brought to the attention of those working with magnetic field measurement problems. This tube measures one component of the ambient field. Preliminary results show that when operating with a dynamic range of several gauss: (1) the sensitivity is better than one gamma; (2) the frequency response is from dc to better than ten kilocycles; and (3) the stability is better than one gamma over ten minute periods. The essential improvement of this tube over other electron beam magnetometers is in its anode which senses changes of the order of 10^{-7} cm in the position of the beam. This tube appears to be suitable for use in magnetic aspect and total field measuring problems in rockets, as well as for more conventional applications.

Edwin J. Chernosky (Geophysics Research Directorate, Air Force Cambridge Research Center, Cambridge, Mass.) The Day-to-Day Variability of Magnetic Activity--The C-figure, the K-index, the u-measure, etc., are indicators of the temporal variability of the geomagnetic field. This study evaluates the temporal variability of one of the variability measures. To make this investigation, arithmetic sums of the differences (ΔC) of the successive daily international C-figures (1884-1951) are determined for one-month and for longer periods. Semiannual peaks in variability are found to occur at about March and October as in the C-figures and others. Unlike C, however, 12-month means of ΔC have minimum values within four months of each of the last four sunspot minima. Evidence for a 22-year cycle is found in ΔC insofar as decreased variability rather than increased variability is found at alternate sunspot maxima. A secular minimum in ΔC occurs at about the turn of the century.

Frank Chew (Marine Laboratory, University of Miami, Coral Gables, Fla.) On the Offshore Circulation and a Convergence Mechanism in the Red Tide Region off the West Coast of Florida--The offshore water is shown to move as a single column. The sloping bottom and the equation of continuity are then applied to show the existence of a horizontal convergence mechanism which, over a period of several weeks, may effect an increase in concentration of floating organisms or detritus or both some several times its initial value. The southbound current in the 'loop' portion of the current which enters the Gulf through the Yucatan Channel is thought of as a Rossby jet driving the cyclonic eddy offshore. Consideration of the abbreviated vorticity equation, together with the fact of sloping bottom, show that the southeastern quadrant of the cyclonic eddy possesses increasing negative vorticity and hence the organisms previously concentrated will tend to wash ashore. Some considerations of the effects of wind are also included.

W. E. Clark (Ground Water Branch, U. S. Geological Survey, Austin, Texas) Forecasting the Dry-Weather Flow of Pond Creek: A Progress Report--A method for forecasting the dry-weather flow of Pond Creek, in west-central Oklahoma, is outlined in this paper. Pond Creek drains an area of 319 sq mi above the gaging station. Its dry-weather flow, somewhat modified by the effects of evapotranspiration and antecedent overland runoff, is maintained by discharge of the ground water contained under water-table conditions in the Rush Springs sandstone. Multiple correlations are computed relating the dry-weather flow to ground-water levels as shown in a well and to a factor indicative of evapotranspiration. A method for forecasting the factor indicative of evapotranspiration and one for forecasting the ground-water levels during dry weather are given; the result is a method for forecasting the dry-weather flow of the creek. Results of forecasts of dry-weather flow for seven and 21 days are given and compared with the flows actually measured. The flexibility of the technique is illustrated by extending a forecast for several months.

Robert Clayton (California Institute of Technology, Pasadena, Calif.) Oxygen Isotope Abundances in Quartz and Calcite--The ratio of O^{18}/O^{16} has been determined in natural samples of quartz and calcite occurring together in rocks formed under a wide range of geological conditions from sediments to pegmatites and contact metamorphic rocks. There is a considerable isotopic fractionation between these two phases, amounting to 0.80 pct at low temperatures and decreasing to 0.20 pct in the highest temperature rocks analyzed. The fractionation can be measured with an accuracy of 0.02 pct. Thus, with suitable samples, the isotopic fractionation can be used as a geological thermometer. The relative temperatures of formation, as deduced from the isotopic fractionation, are in complete agreement with the geological evidence. Conclusions can also be drawn concerning the amount of water present in hydrothermal action, and an estimate of its isotopic composition can be made.

W. Compston and P. M. Jeffery (University of Western Australia, Nedlands, Western Australia) The Carbon Reservoir and Isotope Abundance Fluctuations--Recent studies by various groups of the abundance ratios of the stable carbon isotopes in nature have established ranges for the variations found in samples from different geologic sources. In order to account for these variations it has been necessary in some cases to postulate a constant isotope composition of the carbon reservoir formed by the atmosphere and hydrosphere. No systematic change in the carbon isotope abundance of this reservoir has so far been reported. It appears likely, however, that small abundance changes have occurred during the course of geologic evolution and an investigation is in progress to establish the validity or otherwise of this premise. Severe restrictions on the types of sample which can be used for such a study limit the amount of data available. The results to date indicate a maximum variation since Cambrian times in the stable carbon isotope abundance of the atmosphere-hydrosphere reservoir of the order of one half a per cent.

Gilbert Corwin, L. D. Bonham, M. J. Terman, and G. W. Viele, Jr. (U. S. Geological Survey, Washington 25, D. C.) Geology of Pagan, Mariana Islands--Pagan, largest of the Northern Mariana Islands, western Pacific Ocean, consists of two active volcanic centers located within calderas that are connected by a high rugged isthmus. The northern caldera, 3 1/2 miles in diameter, has one large central cone which last erupted in 1925. The smaller southern caldera, 1 1/2 miles in diameter, has several large cones; the last activity was in 1930. Relatively recent intracaldera flows of basalt are extensive north, east and south of the northern volcano; ash is concentrated to the west (leeward). The flows include both aa, derived chiefly from the summit, and pahoehoe, erupted mainly at the base of the cone. Where the lavas have flowed over cliffs, textural changes, including transitions from pahoehoe to aa, have taken place. The southern volcano is flanked on all sides by aa flows. The pyroclastic deposits are of many fragmental and textural types; most were deposited subaerially.

Harmon Craig (Institute for Nuclear Studies, University of Chicago, Chicago, Ill.) and Donald E. White (U. S. Geological Survey, Menlo Park, Calif.) The Use of Calcite as an Isotopic Geothermometer--In conjunction with a study of the deuterium and oxygen 18 content of thermal waters, we have been investigating variations in the O^{18} content of calcite from hot springs and vein deposits for possible use in geothermometry. The normal range of O^{18} variation in natural waters, some 3.5 pct, can introduce an error of more than 100°C in the estimated temperature of formation unless corrected for. However, it is possible to use the C^{13} content of the carbonate as an indication of variations in H_2O^{18}, since C^{13} and O^{18} in a suite of calcites should show a direct relationship if temperature has been the only variable during their formation. This paper is a progress report on a systematic study of surface and drill core samples of calcium carbonate from Yellowstone Park and Steamboat Springs, Nev., where the isotopic variations in the thermal waters have been studied in detail. The O^{18} content of modern material shows a direct variation with temperature of formation, and isotopic data on both O^{18} and C^{13} indicate temperatures for subsurface deposits in accord with the geothermal gradient. It appears that temperature determinations to varying degrees of precision can be made by this method, depending on various factors to be discussed, though several problems remain to be settled.

A. P. Crary and Irene Browne (Air Force Cambridge Research Center, Cambridge, Mass.) Arctic Ice Island Oceanographic Observations--The ice island T-3 was abandoned by the USAF May, 1954, at 84°30'N, 82°W after 26 months of weather observations and geophysical studies over approximately 500 miles of drift in the Central Arctic Basin. Oceanographic studies included bathymetry, ocean temperatures and salinities, currents and ice movement studies, marine biology, bottom coring, and a limited amount of sub-bottom geophysical operations, with the Air Force Cambridge Research Center, Arctic Aeromedical Laboratory, and Woods Hole Oceanographic Institution actively participating. A brief resume of the results presently available is given. Some data available concerning recent Soviet expeditions to the central Arctic are also presented. Oceanographic studies made along the northern shores of Ellesmere Island during a joint Canadian-United States expedition during the summer of 1954 are briefly discussed.

T. Cromwell, P. Horrer, J. Reid, M. Schaefer, and W. Wooster (Scripps Institution of Oceanography, La Jolla, Calif.) Plans for Joint Operations in the Pacific during 1955--The Scripps Institution of Oceanography will participate in two cooperative surveys of large areas of the Pacific Ocean during 1955. In August, a fleet of oceanographic vessels will survey the northern Pacific from North America to Japan and from 20°N to the Aleutian Islands on NORPAC expedition. Agencies of the United States, Canada, and Japan will take part in the cruise whose function is to survey the area with hydrographic casts for temperature, salinity, oxygen, and phosphate. Surface currents by GEK and zooplankton samples will be obtained. The observations will furnish coverage of the largest ocean region yet attempted 'synoptically.' During October-December, the Scripps Institution, the Inter-American Tropical Tuna Commission, the Pacific Oceanic Fishery Investigations of the U. S. Fish and Wildlife Service and, tentatively, a vessel of the Peruvian Navy, will survey the eastern tropical Pacific on EASTROPIC expedition. Data concerning the circulation, chemistry, and plankton of the Equatorial Current System will be obtained. In addition, features of special interest will be surveyed oceanographically in detail, including a rich tuna-fishing ground off Costa Rica, regions where abrupt changes in water properties are known to occur southwest of the tip of Lower California and near the Galapagos Islands, and measurements of the Equatorial Undercurrent using drogues.

G. L. Davis, G. W. Weatherill, and L. T. Aldrich (Geophysical Laboratory and Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.) Age Measurements on Minerals from Granite--The application of the Rb-Sr and K-A decay schemes to mineral age determinations previously has been confined for the most part to selected minerals from pegmatites. The purpose of this paper is to report the extension of these methods to the mica and feldspar fractions of granites. The mica and feldspar fractions of four granites have been analysed. In the micas the radiogenic Sr^{87} was found to be more than 90 pct of the total Sr^{87} present. This is a much larger fraction than has been reported previously and allows the determination of radiogenic Sr to be made with considerable accuracy. In the two cases where the Rb-Sr and K-A determinations of age have been made on the same micas, the former are about ten per cent higher than the latter. These ages have also been measured on a K-feldspar concentrate. The Rb-Sr age agrees within experimental error with that determined for the biotite from the granite, while the feldspar K-A age appears anomalously low.

G. E. R. Deacon (National Institute of Oceanography, Wormley, Surrey, England) The *Discovery* Investigations in the Southern Ocean--The primary object of the investigations was to provide a scientific basis for the regulation of the whaling industry, and it included the pursuit of enquiries into the ecology, distribution and fluctuations of the plankton organisms which provide the whales with food. Most of the oceanographic survey has been done by the R.R.S. *Discovery II* which was specially built for the purpose and by the R.R.S. *William Scoresby* designed for whale-marking and fishery work. Fourteen expeditions have been sent to the Antarctic Ocean over a period of 27 years, and unique experience and comprehensive results have been obtained. The physical and chemical data have been published in the *Discovery* Reports and increasing use is being made of them. The investigations are being continued under N. A. Mackintosh at the National Institute of Oceanography.

George W. DeVore (Department of Geology, University of Chicago, Chicago, Ill.) Surface Chemistry and Mineral Association--In highly polymerized minerals, the degree of polymerization at the mineral surface is reduced by various surface reactions. Through polymerization interruption, quartz surfaces may have the composition of Si_3O_7, essentially the composition of the Si-O groups in K and Na feldspar. Further polymerization interruption produces a quartz surface of Si_4O_{10} composition, equivalent to Si-O groups in talc and micas. K and Na feldspars can undergo polymerization interruption to produce Si_4O_{10} groups on the surface and the Ca-rich feldspars can break up to give Si_4O_{11} and Si_4O_{12} groups on the surface. By polymerization interruption, anions on the surface take on the chemical characteristics of anions associated with less polymerized minerals. The similarity of anions between different minerals, which permits nucleation and crystal growth, is suggested as the reason for the common coexistence of quartz with feldspar, quartz with muscovite, feldspar with biotite, and Ca-rich feldspar with hornblende and pyroxene. The type of mineral contacts, the distribution of minerals in a rock, and the ratio of one mineral to another is interpreted as the result of the interface energy of the mineral contacts. The role of ionic polarization as a control on the degree of polymerization interruption, the interface energy, and the nucleation of different minerals on a surface is discussed.

Frank B. Dinwiddie (Nags Head, N. C.) Some Aspects of Waterspout Behavior at Nags Head, N. C.--Description is made of a situation leading to the anticipation of tornado-waterspout formation, of three waterspouts which subsequently formed, and of the observer's passage through the third spout. The development of waves in a straight band of cumulo-nimbus, and the development of tornado cyclones within the waves, preceding tornado genesis, is described and analyzed. Structure of the third vortex near the surface is examined and interpreted in detail. Its principal parts are classified as: convergence disk, jet cone, core wall, and outfall ring. An appropriate pressure distribution, based on the concept of surface-frictional breakdown of gradient equilibrium, is proposed. Strong surface convergence, non-cyclonic on its periphery, and increasingly cyclonic toward the center, is demonstrated. The effect of the work of imparting this cyclonic motion is considered. The cushioning effect of upflow outside the core wall on descending objects is shown. The jet within the core wall appears to be the principal lifting mechanism. Its lifting force diminishes rapidly with height. Statements summarizing the relevance of these observations and interpretations to general tornado theory are offered in conclusion.

Philip C. Doran (U. S. Coast nad Geodetic Survey, Washington 25, D. C.) Recent Developments in Geodesy--A summary is given of the new equipment and techniques which have broadened the scope of geodetic activities in recent years, including various applications by the Coast and Geodetic Survey and other organizations. Principal topics are: (1) extension of horizontal control into remote areas by means of modern transport facilities, (2) direct distance measurements by electronic methods, (3) studies of deflections of the vertical and geoid undulations, (4) gravity meter calibration and international ties, and (5) application of high-speed computing methods. Also included is an outline of problems which have recently arisen concerning large-scale crustal movements, with discussion of possible methods of solution.

Harold E. Edgerton (Massachusetts Institute of Technology, Cambridge, Mass.) Calypso Oceanographic Expeditions--Founded by J-Y Cousteau and directed by the French National Center for Scientific Research, Calypso Expeditions has added free diving to classic marine instrumentation. The Calypso research team, which with its Marseille center Office Francaise de Recherches sous-Marines, numbers fifty divers, seamen and technicians, employs the 320-ton research vessel, MS Calypso, and a 60-foot converted trawler, Espadon. The group employs underwater still and cinecameras and submersible television apparatus in both handheld and automatic depth units on cables. Carrying scientific parties up to ten people, Calypso since 1951 has undertaken a general monography of Abu Latt island in the Farsan Bank of the Red Sea; underwater excavation of a Greek cargo ship, sunk circa 205 B. C., off Marseille: a geodetic survey of the bottom of the Persian Gulf off Trucial Oman: hydro-archeological surveys in the Aegean and Ionian Seas; and many sorties of two or three weeks in the Mediterranean for biological, geological, and chemical studies. A continuing investigation of the deep scattering layer and bottom phenomena is being made with automatic electronic flash cameras built at Massachusetts Institute of Technology. About 30,000 photographs have been taken in the Mediterranean Sea, the Red Sea, and the Indian Ocean. These cameras are also used on the Franch Navy bathyscaphe FNRS 3. Camera stations of 3000 ft down have been attained. The DSL photo evidence has not shown a clear case for sonar interference by organisms. Photos made above and below the diffusion layer have often shown as many micro-organisms, siphonophores, medusas, shrimps, etc., as in the layer itself. No larger athletic animals such as squids have been found in the photographs of the DSL.

W. M. Elsasser and H. Takeuchi (Department of Physics, University of Utah, Salt Lake City, Utah) Non-Uniform Rotation of the Earth and Geomagnetic Drift--The transmission of mechanical forces of the magnetic field through the top layers of the core and into the mantle is analyzed. It is shown that moderate fluctuations of the toroidal field near the boundary of the core are adequate to produce the observed variations in the Earth's rate of rotation. A simple model of the boundary layer of the core is worked out and it is shown that the angular velocity, on going down from the boundary of the core, must first decrease and then increase again, in agreement with the observations on the westerly drift and with the dynamo theory.

Jack F. Evernden (Department of Geological Sciences, University of California, Berkeley, Calif.) Finite Strain Theory and the Earth's Interior--It is shown that, contrary to published opinion, the Poincare-Brillouin approach to finite elastic strain theory leads to equations completely equivalent to those obtained by the Murnaghan-Birch approach. Any apparent differences are simply a matter of Lagrangian versus Eulerian approach and of definition of the strain invariants. Applying the Brillouin pressure-strain equation to the Earth's interior, that is, Bullen's data), it is evident that there is a multiplicity of possible conclusions. The relative accuracy of the determined parameters is discussed and it is concluded that the Bullen data can be interpreted to mean a lower mantle with $\rho_0 = 4.0$ gm/cm^3, $K_0/\rho_0 \cong 33$ km^2/sec^2, and an outer core having $\rho_0 = 6.75$ gm/cm^3, $K_0 \cong 1.2 \times 10^{12}$ dynes/cm^2.

Maurice Ewing and Bruce C. Heezen (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) Deep Sea Expeditions of the Vema--Research Vessel Vema, a 200-ft schooner operated by Columbia University (Lamont Geological Observatory) has made six expeditions in the Atlantic Ocean, Gulf of Mexico, and Caribbean Sea since she sailed on her first scientific cruise in April, 1953. The scientific observations included: topographic studies with a newly developed precision depth recorder; sediment sampling with piston corers; rock dredging; bottom and mid-water photography with a multi-shot electronic flash camera; seismic investigations of the sea floor by refraction and reflection techniques; continuous measurement of the total intensity of the Earth's magnetic field; large volume water sampling at serial depths for radiocarbon analysis; bathythermograph observations, both standard and deep; plankton sampling, and miscellaneous minor programs. On her first cruise Vema accompanied Atlantis (Cruise 185) on an expedition to the Caribbean and Gulf of Mexico. On Cruise 2 during the summer of 1953 a study was made of the continental rise and abyssal plain south of Newfoundland. Vema Cruise 3 was a five-month intensive investigation of the Gulf of Mexico. On Cruise 4, July-September, 1954, the investigation of several seamounts, the study of the Portuguese submarine canyons and adjacent abyssal plains, the collection of large volume water samples from great depths, and the discovery and investigation of a new mid-ocean canyon were important programs. Cruise 5 featured an intensive bottom sampling program on the Bermuda pedestal. Cruise 6 took the Vema to the Puerto Rico area where an investigation of the Puerto Rico Trench and abyssal plains was undertaken.

Maurice Ewing, Frank Press, and William Donn (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) Air-Coupled Surface Waves--Examples of coupling of atmospheric disturbances to surface waves are presented. Tide gage disturbances following the eruption of Krakatoa, air-coupled flexural waves and groundroll, and the Lake Michigan wave of June 26, 1954, are among the examples discussed. Preliminary results of model studies are presented.

L. A. Farrer (Meteorology and Regulation Section, Office of the District Engineer, U. S. Corps of Engineers, Jacksonville, Fla.) Effect of Hurricane Winds on Water Levels in Lake Okeechobee--Hurricane winds have raised the water surface at the shore of Lake Okeechobee more than ten feet above the level pool. In order to obtain reliable information on wind velocities, waves and water surface profiles during hurricanes, the Corps of Engineers has established and operated 12 gaging stations in and around the lake. Data obtained at those stations during the 1949 hurricane are presented and methods of computing wind tides are discussed.

V. C. Fishel (Ground Water Branch, U. S. Geological Survey, Lawrence, Kans.) Long-term Trends of the Ground-Water Levels in the United States--Ground-water levels at the end of 1954 were at or near record-low stages throughout most of the southern two-thirds of the United States. These low stages, like those of the early 1930's, have led to frequent expression of the opinion that the water table throughout the country is continuously falling and that we are gradually exhausting our ground-water supplies. A good record of changes in ground-water levels is being obtained by the United States Geological Survey and cooperating State agencies from periodical measurements of nearly 20,000 observation wells. The records of some of these wells extend back for 50 years. Many records are available for the period beginning in 1934. These long-term records indicate that in some areas the ground-water supply is overdeveloped, but in the great majority of areas the stage of the water levels correlates with the precipitation. Much of the country has been in a drought and the water levels are at a low stage. When the precipitation increases, as it is bound to do eventually, the water levels will return to higher stages.

Scott E. Forbush and E. H. Vestine (Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.) Daytime Enhancement of Size of Sudden Commencements and of Initial Phase of Magnetic Storms at Huancayo--A diurnal variation in the ratio of the size of sudden commencements (sc) at Huancayo to that at Cheltenham was found by Sugiura. Evidence was presented by Vestine indicating daytime augmentation at Huancayo, of the initial phase of magnetic storms. Ferraro and Unthank as well as Sugiura indicated the similarity of the diurnal variation in the average size of scs at Huancayo to the diurnal variation of H at Huancayo. Applying statistical tests we find from 428 scs that the frequency of occurrence is independent of time of day. Statistical tests indicate that the average size of scs and of initial phase are both significantly greater during the daylight hours at Huancayo, showing that previous objections raised by Ferraro seem unwarranted. Also from 102 sudden commencements occurring between 8h and 14h, 75° WMT at Huancayo, we find that the average size of scs is greater for those days with the larger diurnal variation in H. Furthermore, the result is statistically significant especially since the average size of scs was about 50 pct greater for the group of days with 50 pct greater diurnal variation in H. If the size of scs at Huancayo is 'corrected' for the diurnal variation in H, the resulting sizes are on the average comparable with those at Watheroo. The relation of daytime enhancement of the size of scs to Sq in H at Huancayo indicates that the current system responsible is closely associated with the electrojet effect responsible for the large diurnal variation in H at Huancayo. The effects found do not appear to be readily explicable on the basis of the Chapman-Ferraro theory of magnetic storms. One possibility that is being examined is that the electric currents in the atmosphere near Huancayo are driven by the electrojets of polar regions.

G. D. Garland (Department of Physics, University of Alberta, Edmonton, Canada) and L. G. D. Thompson (Dominion Observatory, Ottawa, Canada) Geological Implications of Gravity Anomalies over the Grenville and Northern Appalachian Regions of Quebec--The results of gravity observations by the Dominion Observatory in Quebec, south of latitude 52°, have shown wide variations in Bouguer anomaly within relatively short distances. An almost continuous narrow belt of positive anomalies, ranging up to 40 mgal, lies along, and south of, the northern limit of the Appalachian province. The association of this effect with known areas of ultrabasic rocks suggests the presence of a sheet of such material, possibly brought to the surface by thrusting. Gravity effects along the northern boundary of the Grenville province, which has been described as a thrust fault, are examined, but no such striking effect is observed. By contrast, certain trends appear to cross the boundary without interruption. Within the Grenville itself, the most outstanding features are the large negative anomalies, ranging to minus 80 mgals, associated with known bodies of anorthosite. The significance of these observations in relation to theories of the origin of anorthosite is discussed.

R. M. Garrels, W. C. Krumbein, and H. A. Slack (U. S. Geological Survey, Washington 25, D. C. and Northwestern University, Evanston, Ill.) Transfer of Energy and Materials through Rocks--It is observable in many geologic processes that the quantity of matter or energy transported or transferred during the process is a function of some cross-sectional area, of time, of a constant of proportionality K, and of a potential gradient. Movement of ground water, development of alteration zones adjacent to veins, and solution and growth of crystals are examples of such phenomena. The underlying form of the controlling function is the same in all of these processes. As long as steady state conditions prevail, the mathematical treatment is straightforward. In most geological situations steady state conditions are attained only rarely, with the result that the mathematical treatment may become highly complex. Fortunately, solutions of analogues of some of the more complex problems are available from the literature on heat and electricity. For example, many problems related to the diffusion of ions or molecules through porous rocks can be solved by use of Hottel charts developed for heat transfer. An important parameter in the mathematical function is the constant K, which represents the coefficient of conductivity, diffusion, etc. This coefficient is descriptive of the process, but its evaluation is difficult in some geological problems. In such instances the use of a probabilistic model permits consideration of K as a variable having its own mean and variance. Probabilistic models have already been applied to diffusion processes, and it is believed that a similar approach in other instances will permit use of field data as well as controlled laboratory data as means of approximating complex geological relationships.

John R. Gerhardt and Kenneth H. Jehn (Electrical Engineering Research Laboratory, University of Texas, Austin, Texas) On the Problem of Determining the Spatial Distribution of Small Scale Atmospheric Phenomena from Point Measurements with Application to the Field of Radio Meteorology--Th problem of predicting or characterizing the instantaneous spatial distribution of such parameters as temperature or moisture over some volume of the atmosphere has a considerable practical application in such fields of study as the diffusion of contaminants, the transfer of heat, and the atmospheric propagation of radio signals. The last of these represents a peculiarly complex situation since the received signal strength variations, for instance, are a function of a spatially integrated atmospheric microwave refractive index distribution. While no direct correlation is thus possible between simultaneous meteorological and radio measurements, average statistics of the two types of observations can be compared under certain conditions. In homogeneous atmosphere, for instance, the mean time and space scales and intensities of the turbulent component of the refractive index distribution can be used to obtain indications of the RMS value and power spectra of the recorded radio variations. The non-homogeneous case, however, cannot be analyzed directly through meteorological sensing elements and the eventual results may be the direct employment of propagation observations as a measure of the smaller scale state of the atmosphere. Data are presented showing some of the kinds of refractive index variations that exist in the troposphere and the observational requirements needed to obtain even a minimum correlation are outlined.

N. C. Gerson (Geophysics Research Directorate, Air Force Cambridge Research Center, Cambridge, Mass.) Observations on the Ionized Aurora--Radio wave observations of the ionized aurora were made during a three-year period from January, 1949, to December, 1951. Observations were made at a frequency of 50 mc/sec using rather low transmitted power. On a monthly base the greatest frequency of occurrence was found during April with a secondary maximum during October. While the radio-wave observations permitted the surveillance of the ionized aurora throughout the 24-hour period, it was found that a minimum in auroral activity occurred from about 08h 00m-13h 00m local standard time. A diurnal maximum was found from 18h 00m-21h 00m.

Bruce Gilchrist (Electronic Computer Project, Institute for Advanced Study, Princeton, N. J.) Observational and Transmission Requirements for Numerical Weather Prediction--The general problem of determining the data requirements for a numerical forecasting system is discussed and the difficulty of specifying rigid requirements is demonstrated. Estimates of the required geographical spacing of upper-air observing stations are discussed in the light of recent experiments in objective analysis. The time spacing of observations is also discussed and a suggestion made that the time spacing should be allowed to vary as circumstances demand. The importance of having a communications system of comparable efficiency to the forecasting one is emphasized and ways of improving the present communications system are suggested. Finally, a central computing center is envisaged which would not only make forecasts, but also control the observing and transmission of meteorological information.

Robert A. Gilcrest (Department of Oceanography, Texas A and M College, College Station, Texas) An Approach to the Problem of Prediction of the Net Weekly Ocean Temperature Change--Computing equations which are being developed to predict the temperature structure in a two-layer ocean, excluding water over continental shelves, are presented together with the underlying assumptions. The factors being taken into account are: (1) In determination of the temperature in the mixed layer--advection, mixing of water through the interlayer interface, radiation, and evaporation; and (2) In determining the mixed-layer depth--divergence of water in the mixed layer, and mixing of water through the interlayer interface. The manner of application of these equations to processed oceanographical and meteorological data for the North Atlantic will be discussed. The periods of computation are September, October, and November of 1949 and 1951. The results of computations of divergence of surface water and evaporation are given. The future direction of this research is indicated.

S. S. Goldich and A. P. Ruotsala (University of Minnesota, Minneapolis, Minn.) Igneous Rock Series of Minnesota--A recently completed compilation of the chemical analyses of igneous rocks of Minnesota is the basis for reexamination of older ideas on the origin of these rocks. Concepts of petrogenesis are considered in the light of the broad implications of the chemical data rather than with regard to individual occurrences or specific problems. Forty-two analyses of Keweenawan rocks from the Lake Superior region of Minnesota are used for a comparative study of the diagrams commonly employed by petrologists to illustrate variations in rock series. The ordinary silica-variation diagram serves as well for the single group as the more elaborate Larsen diagram or its modification by Nockolds and Allen. Analyses of older granites and related rock types (Laurentian and Algoman) show trends different from those of the Keweenawan series, suggesting that different processes were involved, if not completely independent modes of origin.

D. T. Griggs, G. C. Kennedy, and W. S. Fyfe (Institute of Geophysics, University of California, Los Angeles, Calif.) A Simple Apparatus for High Pressure and Temperature--The principle of Bridgman's shearing apparatus has been exploited for studies of phase equilibria at high temperatures. The pressures attainable decrease from 100,000 bars at room temperature to 50,000 bars at 600°C, and 10,000 bars at about 1000°C. The sample, in powder form, is compressed between two cemented carbide pistons. The whole assembly is heated by an external furnace. Pressure is known to about ten per cent, and temperature to about 10°C. Reactions occur at unexpected speed. For example, jadeite has been formed from analcite and quartz at 550°C in two hours. Other examples will be mentioned.

Gordon W. Groves (Scripps Institution of Oceanography, La Jolla, Calif.) Oscillations in Sea Level with a Period of a Day or More--Simultaneous records of hourly tidal heights from about

50 tide stations are examined by means of a numerical filter, which essentially eliminates all oscillations whose period is a day or less. The diurnal and higher species tides are reduced in amplitude by a factor of 10^{-4} by this means. The resultant records are compared with meteorologic data and, where possible, with oceanographic data. On the average, the sea-level oscillation has a rms value of 20 cm, about 2/3 of which is due to direct response to variations in atmospheric pressure. The remaining portion is related to local winds, long-period tidal constituents and other causes.

Norman R. Hagen (Plans and Program Management Office, U. S. Weather Bureau, Washington, D. C.) Notes on the Record Losses from 1954 Hurricanes--Hurricanes Carol, Edna, and Hazel together were responsible for breaking many meteorological records, and far surpassed previous annual records for damages by North American severe storms. Hurricane Carol on August 31, 1954 alone caused damage amounting to nearly 500 million dollars. Comparisons with previous losses, some storm high-lights, and damage assessment problems are discussed briefly.

Mahdi S. Hantush (New Mexico Institute of Mining and Technology, Socorro, N. M.) Analysis of Data from Pumping Tests in Leaky Aquifers--Three graphical methods are outlined for determining the leakage factor and the coefficients of storage and transmissibility of an effectively infinite leaky artesian aquifer. The procedure is based on the solution by Hantush and Jacob of the non-steady flow towards a steadily discharging well from an infinite leaky aquifer. Applications of these methods are illustrated by treating pumping tests data carried out in the Roswell artesian basin in New Mexico

G. Earl Harbeck, Jr. (U. S. Geological Survey, Denver, Colo.) The Lake Mead Evaporation Study--The study of evaporation from Lake Mead, a cooperative project of the Departments of Interior, Commerce, and Navy, was an outgrowth of the comprehensive survey of Lake Mead made in 1948-49 and the Lake Hefner studies made in 1950-51. Techniques developed and tested at Lake Hefner were used to determine evaporation from Lake Mead during the period March, 1952 to September, 1953. It was considered impracticable to determine evaporation from Lake Mead from records of inflow, outflow, and change in storage because small percentage errors in measuring these items might result in large errors in the residual and because of the uncertainty concerning unmeasured inflow. Recourse was necessary, therefore, to the energy-budget and mass-transfer methods tested at Lake Hefner. On an annual basis the results obtained with the energy budget agreed closely with those obtained using the quasi-empirical mass-transfer equation developed for Lake Hefner. Marked seasonal deviations were noted however, and were attributed to the effect of atmospheric stability, which was insignificant at Lake Hefner, a much smaller lake. An empirical seasonal adjustment was made using a stability parameter proportional to the Richardson number. During the water year ending September 30,1953, evaporation from Lake Mead was found to be 875,000 acre-feet, equivalent to a depth of 85.5 inches or 7.1 feet over the reservoir area. An empirical equation was derived for computing current evaporation from Lake Mead on a continuing basis.

R. I. Harker and O. F. Tuttle (Division of Earth Sciences, Pennsylvania State University, University Park, Pa.) Some Experimental Data Applicable to the Metamorphism of Siliceous Limestone and Dolomite--Attempts are being made by experiment to determine the nature of the reactions which take place with varying temperature and pressure of CO_2 in the system CaO-MgO-SiO_2-CO_2. Evidence concerning the reactions involved was previously derived almost entirely from the petrographic studies of thermally metamorphosed contact rocks. More precise information is now available on the thermal dissociation of some of the carbonates in the CaO-MgO-CO_2 system and on the formation of wollastonite, monticellite and akermanite by decarbonation reactions. Between 10,000 and 40,000 psi, calcite and quartz become unstable together and react to form wollastonite and CO_2 at temperatures approximately 150° C below those at which dolomite dissociates with the formation of calcite, periclase, and CO_2. The two P_{CO_2}-T curves for the formation of monticellite and akermanite from calcite, diopside and forsterite lie between 850 and 1000° C at 10,000 psi. Synthetic spurrite has been prepared in the presence of excess CO_2. The importance of possible reactions taking place in natural rocks in CO_2 deficient regions cannot be ignored. Akermanite, for example, has been found to break down at certain temperatures and pressures (of H_2O) to monticellite and wollastonite.

D. Lee Harris (U. S. Weather Bureau, Washington 25, D. C.) The Effect of a Moving Pressure Disturbance on the Water Level in a Lake--Seven persons were drowned by a sudden and unexpected rise in the level of Lake Michigan along the Chicago shore line about 08h 25m CST, June 26, 1954. A pressure jump line with a speed of about 60 mph had passed across the city from west to east about 06h 30m CST. In 1929, Proudman considered the effect of a moving atmospheric disturbance on the water level in an infinitely long narrow canal of constant depth, and showed that, in this model, the amplitude of the disturbance in the water would tend to infinity as the speed of the atmospheric disturbance approaches $\sqrt{gH}$, the speed of shallow water gravity waves in the canal. The velocity of this pressure jump line was approximately equal to $\sqrt{gH}$ over a large part of southern Lake Michigan, and the unusually large amplitude of the water level disturbance in Lake Michigan on June 26, 1954 has been attributed to this fact by several authors. The hydrodynamic theory of the effect of a moving pressure disturbance on the water level in a lake of simple geometric shape will be developed in this paper and the results will be compared with the Chicago wave of June 26, 1954.

Harold B. Harshbarger (U. S. Weather Bureau, Washington, D. C.) Climatological Requirements for Meteorological Observations--In recent years observational programs have been dictated largely by meteorological operational requirements of the moment; this practice at best results in masses of residual data which are frequently only partially satisfactory for climatological purposes because of the frequent changes in station locations or instrumental exposures. Inadequate as this practice has been in the past, the future appears even more grim. Increased use of the automatic type of station for making and transitting observations without plans for recording these data will result in their loss for climatological purposes. It is important that our current observational program be examined and that more consideration be given to climatological requirements. It is necessary that action be taken to assure adequately long records of basic instrumentally and visually observed data from a planned network of locations at which homogeneous conditions are maintained. Consideration must also be given to recording and collecting additional climatological data such as soil temperature, soil moisture, evaporation, and dew. Likewise the collection of new types of records of certain phenomena observed in the areal sense now appears feasible. By the use of such data it would be possible to approach some of our climatological problems more directly than was hitherto possible via synoptic analysis. This is particularly applicable to some of the more discontinuous parameters such as cloud cover and precipitation.

Leonard F. Herzog and William H. Pinson, Jr. (Department of Geology and Geophysics, Massachusetts Institute of Technology, Cambridge, Mass.) The Rb and Sr Content and Geologic Age of Certain Biotites, and a Correction to the 'Cosmic' and 'Crustal' Abundances of Rb--The Rb and Sr content and Sr isotope composition of several igneous-rock biotites and one phlogopite has been determined by the mass spectrometric isotope dilution technique. Certain samples previously analyzed at the Department of Terrestrial Magnetism by one of us (LFH) for Sr isotope content have been re-run and the low Sr^{87} enrichments reported then confirmed. Isotope dilution Rb analyses of these samples, meteorites, and geologic element-abundance standards necessitate downward revision of currently-accepted values for 'cosmic' and 'crustal' Rb abundance by a factor greater than two. The accepted Rb/K and Rb/Sr ratios, it follows, are similarly lower (new 'cosmic' Rb/K $\approx$ 1/300 and new Rb/Sr $\approx$ 1/5). This result corroborates the previously announced finding that the rate of variation of Sr^{87} during geologic time due to Rb^{87} decay indicates a Rb/Sr ratio closer to 1/5 than to 1/1. A large number of published optical spectrographic Rb analyses are in error by a similar factor and can be corrected on the basis of these analyses.

Victor F. Hess, Vincent J. Kisselbach, and Henry A. Miranda, Jr. (Fordham University, New York 58, N. Y.) Beta Rays from the Atmosphere--A recent series of measurements of the gamma ray ionization due to radioactive products in the air yielded a value in excess of the expected amount by a factor of five. Since, to the authors' knowledge, direct measurements of the beta-ray contribution from the same source have never been made so far, it was felt that such a determination would not be without interest. Two identical beta-ray ionization chambers being available, a differential arrangement, in connection with a Lindemann electrometer, was employed. A preliminary series of measurements was performed in the fall of 1954, to be continued in the spring of 1955. The data collected to date yield a value of 0.9 I. This can by no means be considered a representative value, since relatively few measurements were made, and these only in two locations. According to a computation made in 1934 by the senior author, the products of radon alone in the air yield an expected beta-ray ionization of only 0.02 I. Our preliminary results thus seem to indicate that semi-permanent beta-ray contamination in the atmosphere has developed in recent years.

Thomas J. Hickley, Richard R. Ross, and John J. McCue (U. S. Coast and Geodetic Survey, Washington 25, D. C.) A Telemeter for Seismic Recording--A Telemeter that uses commerical communications components in a system suitable for seismic recording is described. At the transmitting station, the output of a photo-electric amplifier is used to modulate the amplitude of a 1000 cps signal; this modulated audio signal is used to frequency modulate a commercial VHF transmitter. At the receiving station, the demodulated signal is used to drive a high frequency galvanometer. Results from a test installation of the telemeter indicate the fidelity of reproduction.

R. A. Hirvonen (Ohio State University, Columbus, Ohio) On the Precision of the Gravimetric Determination of the Geoid--The precision of the gravimetric deflections of vertical δ and elevations of geoid N depends on the density of the stations where the gravity has been measured. The entire Earth should be covered, and the uncertainty caused by the existing gaps has been estimated by the author using two hypothetical quantities: probable error of representation of a single observation, and the probable mean anomaly of an empty square. Both are determined statistically as functions of the size of the square. On the basis of the present observations, the probable error of δ will be considerably less than one second and that of N less than ten meters at the points situated in the central parts of Europe or the United States. The gaps which should most urgently be filled by the future observations are pointed out.

Walter Hitschfield and J. S. Marshall (McGill University, Montreal, Canada) A Possible Role of Hail in the Development of Tornadoes--Air masses accompanying the formation of tornadoes are characterized by great dryness above the freezing level, and high humidity below. Hail of moderate to heavy intensity falling through such an atmosphere has been calculated to produce rapid cooling by sublimation above, and by melting lower down. In a matter of minutes the temperature of a near vertical column of air drops several degrees. The corresponding drop in pressure leads to a tendency for radial in-flow of air. This flow leads to rotation, induced by the Coriolis force or otherwise, becoming more and more violent as the radius decreases. The predominant sense of rotation may be expected to be cyclonic in the Northern Hemisphere. The above mechanism is suggested for the initiation of tornadoes, and energy considerations have shown this supposition to be reasonable. Pronounced vertical shear would inhibit the formation of such storms.

Heinrich D. Holland and Robert D. Hardin (Princeton University, Princeton, N. J.) On the Log-Normality of the Distribution of the Elements--Ahrens (1954) has pointed out that the distribution of elements in various rock types and minerals, as well as the ratio of the concentration of two elements in rocks and minerals is often lognormal. It can be shown that for a number of elements, lognormality exists only for a restricted range of rock types, and that in other cases the distribution cannot be lognormal for theoretical reasons. The validity of the law of lognormal distribution is thus limited. It is proposed that the shape of the distribution curves, both lognormal and non-lognormal, reflects the chemical behavior and geochemical history of the elements, and may therefore be of assistance in the study of problems of petrogenesis. The effect on the distribution of the elements of their geochemical coherence, the strength of the fractionation to which they have been subjected, and the number of fractionation cycles which they have undergone is evaluated, and a number of distribution curves are analyzed in terms of these factors.

J. B. Holleyman, J. M. Hand, and A. Caporaso (U. S. Weather Bureau, Washington, D. C.) The 1954 Micro-Network of Washington, D. C., for the Study of Pressure Jump Lines on a Small Scale--The Severe Local Storms Research Unit has completed compilation of data for pressure jump lines that crossed Washington, D. C., in 1954. The data were compiled for a micro-network of accelerated micro-barographs and other instruments, for the metropolitan area of Washington, D. C. A brief case study was made for each situation. Statistics on the pressure jump lines are presented concerning frequency of pressure jump lines during months of the year, the number of lines associated with severe local storms, and the average dimensions of these lines. Outstanding cases are briefly reviewed and small-scale variations of pressure jump lines, as revealed by the micro-network, are shown.

R. E. Holzer and O. E. Deal (Institute of Geophysics, University of California, Los Angeles 24, Calif.) Low Audio-Frequency Electromagnetic Radiation of Natural Origin--Natural electromagnetic radiation in the frequency band between 30 and 110 cycles/sec has been studied with equipments employing both air core coils and a vertical antenna. The measurements were conducted in the Borrego Valley of Southern California remote from sources of artificial interference. Evidence obtained from the mean diurnal variation of signal strength, from the diurnal variation in direction of the signals, and from direct correlation with air-earth current density measurements at sea indicate that the signals are due principally to lightning discharges over the surface of the Earth. The apparent attenuation coefficient of the low audio-frequency signals is sufficiently small that the mean signal strength is roughly proportional to the number of storms in progress when no extensive thunderstorm activity occurs within about fifty degrees of the observing station.

B. F. Howell, Jr. (Department of Geophysics and Geochemistry, Pennsylvania State University, University Park, Pa.) Origin of the Continents--Theories of the origin of the continents may be classified into four groups: (1) differentiation in place; (2) gathering together of an originally universal crust; (3) removal or distruction of a part of an originally world-wide crust; and (4) addition of all or a part of the crustal blocks from an extra-terrestrial source subsequent to the formation of the rest of the Earth. The probability of the latter theory is examined in the light of present knowledge of crustal features and crustal history.

Lester F. Hubert (Scientific Services Division, U. S. Weather Bureau, Washington, D. C.) Frictional Filling of Hurricanes--When a hurricane moves from ocean to land, the surface roughness and wind stress increase which increase in turn causes the surface wind to blow across the isobars at a greater angle. The resulting increase of mass convergence is examined in the light of the Rossby-Montgomery theory on influence of friction on surface flow, and the results are compared to the analysis of fifty years of hurricanes that moved onto coasts of the United States. The filling data are also analyzed to study the rate of pressure gradient decrease in the maximum wind zone. The results of this study indicate that the filling due to frictional effects alone cannot dissipate the dangerous winds of a mature hurricane within the first eight to ten hours after moving onshore.

F. A. Huff (Illinois State Water Survey, Urbana, Ill.) Comparison between Standard and Small-Orifice Gages--During 1953-54, an observational program was carried out to compare the catch obtained from four small-orifice gages with that from the U. S. Weather Bureau standard eight-inch stick gage in shower-type rainfall. Orifice areas of the small gages ranged from 0.50 square inch to 7.07 square inches compared with 50.27 square inches for the eight-inch gage. Results of the analysis, in which storm size and wind speed were taken into consideration, indicate that the small-orifice gages are satisfactory for use in place of the standard eight-inch gage under most circumstances. Comparison with results of a rainfall gradient study indicated that the average rainfall variability in shower-type rainfall within a distance of one mile is generally greater than that observed between any of the small gages and the standard gage at a given site.

F. A. Huff and J. C. Neill (Illinois State Water Survey, Urbana, Ill.) Areal Representativeness of Storm Point Rainfall--The relationship between point and areal mean rainfall in shower-type storms was investigated. Data collected with concentrated raingage networks on areas of 8, 25, 50, 100, and 300 sq mi were used in the study. A regression equation of the general form, $E = K P^1 A^m$, was developed from the data. In this equation, E is the expected measurement error when the point rainfall, P, at the center of a given area, A, is assumed to represent the areal mean rainfall within the given area. Results of this study should have application in the design of hydrological raingage networks and in the evaluation of storm data from existing networks.

Ira A. Hunt (Corps of Engineers, 1027 Eighth Street, Alexandria, Va.) Transfer of Energy by Wind to a Water Surface--The paper gives a derived formula expressing how energy is transferred by wind to the water surface through the mechanism of tangential shear stress and by normal pressure exerted on the wave by the wind. It will be shown that for storm conditions the transfer of energy by normal pressure is actually almost a complete energy input on the water surface. Data are given to show that there is a critical friction velocity where instability of the small surface disturbances occur and the disturbances grow rapidly in size.

Patrick M. Hurley (Massachusetts Institute of Technology, Cambridge, Mass.) Scintillation Spectrometer II: Simultaneous Measurement of Uranium, Thorium, and Potassium in Common Rocks--A method is described for the simultaneous radioassay of the uranium and thorium series and potassium in common rocks, or materials of comparable activity, in which the series are in secular equilibrium. The method is based on the measurement of the counting rate in three bands of the photon energy spectrum derived from the gamma-ray excitation of a scintillation crystal. Two of these bands correspond to the 238 kev gamma of Pb^{212} and the 1.46 mev gamma of K^{40} and the third band is centered in a region in which the count is derived largely from scattered gammas from all the radioactive constituents. Under normal conditions the time required of the analyst for the three determinations is about 15 minutes, and by use of multiple sources the same length of time is sufficient for the count.

J. A. Jacobs and D. W. Allan (University of Toronto, Toronto, Canada) Report on Thermal Investigations Being Carried Out at the University of Toronto--A detailed study of the thermal history of the Earth has been in progress at the University of Toronto for over a year. Allowance is made for the decrease with time in the amount of heat generated from radioactive sources, and a number of Earth models are considered with different concentrations and distributions of the radioactive elements. For these models, both temperatures and heat flows at a number of depths within the Earth and at different times in the Earth's history are presented. In particular it is shown how different initial conditions, and hence different concepts of the origin of the Earth, affect its future thermal history.

Joseph Kaplan (University of California, Los Angeles, Calif.) and G. F. Schilling (USNC-IGY, National Academy of Sciences, Washington, D. C.) Motions in the High Atmosphere--Certain applied requirements such as jet aircraft operation, guided missile flights, and global weather forecasts have shown the needs for meteorological research as well as synoptic studies to include higher and higher altitudes. Although the information received on a day to day basis about meteorology of the stratosphere is yet very inadequate and of a sporadic character, the general tendencies can be analyzed and suggestions can be made for observational requirements in the near future. The present paper discusses latest research results in this respect and presents a critical review of general circulation models as they apply to regions above the tropopause. It is shown that successful attempts have already been made to extend such general circulation models to a true, synoptic picture of meteorological conditions in the stratosphere. To progress further, and to achieve a day by day picture of weather above the troposphere, operational research on specific points is needed and the detailed observational requirements are being shown.

Geoffrey A. Kellaway (Geological Survey and Museum, South Kensington, London, S. W. 7, England) Structural and Geomorphological Effects Produced by the Action of Frost and Ice--The origin of certain landforms in the British Isles and North America are discussed in the light of recent work. The connection between structure deformation, erosion, and sedimentation in Pleistocene times is described with reference to glaciation and areas where severe frost climates are in being at the present time. It is concluded that many British Pleistocene structures have complex histories, and an attempt is made to evaluate the relative importance of the part played by frost and by surface ice or snow in their development.

George C. Kennedy (Institute of Geophysics, University of California, Los Angeles, Calif.) Some Liquidus Temperatures in the System SiO_2-FeO-H_2O--The recent important discovery of Tuttle, England, and Yoder that moderate to high pressures of water sharply lower the melting point of quartz has been confirmed. An additional lowering of the melting point, beyond that effected by pute water is encountered when small amounts of metal oxide, dominantly FeO, are added to the system. The melting point of quartz, with approximately one per cent FeO added, under 900 bars water pressure, is 1000°C. At 1400 bars water pressure, the liquidus in the system drops to 900° At approximately 3000 bars water pressure the liquidus drops to 800°. The small amount of iron oxide lowers the liquidus temperature some 200° below that found in the pure silica-water system. The dry system FeO--SiO_2 has been studied by Bowen and Schairer. The lowest melting point is the Wustite-Fayalite eutectic at 1177°C at a composition of 70.5 pct FeO. The lowest melting point at the silica rich end of the system is 1690°C in sharp contrast to the 800°C liquidus temperature found for the silica rich end of the system under 3000 bars water pressure.

David G. Knapp and James H. Nelson (U. S. Coast and Geodetic Survey, Washington 25, D. C.) A Notable Transient Perturbation on the Magnetograms of January 17, 1955--The severe magnetic storm of January 17-18, 1955 was characterized at College, Alaska, by a relatively moderate phase beginning at about 17h 00m U. T. and lasting about eight hours, during which the hourly means were nearly uniform and the activity consisted for the most part of oscillations almost steady enough to be described as pulsations (period about 4 to 6 minutes, amplitudes around 100 gammas in H). However, there was at 18h 57m an extraordinary isolated pulsation which can be detected on magnetograms recorded at least as far away as Honolulu, Hawaii and San Juan, Puerto Rico. The amplitude of this perturbation was more than 1100 gammas at both College and Barrow, and at these observatories its azimuth was approximately in the geographic meridian, but the pulses were opposite in phase at the two stations. The perturbation was accompanied by a noticeable, widespread enhancement of short-period activity, and also by a sharp rise in H at observatories in low and medium latitudes.

M. A. Kohler, T. J. Nordenson, and W. E. Fox (U. S. Weather Bureau, Washington, D. C.) Evaporation from Pans and Lakes--During the period 1950 through August, 1951 a comprehensive inter-agency evaporation experiment was conducted at Lake Hefner, Oklahoma, by the Departments of Interior, Commerce, and Navy. Major results of the study were released in 1952 and summarized tabulations of the observations were subsequently published in 1954. Continuing evaporation studies conducted by the Weather Bureau have been aimed primarily toward the development of improved methods for estimating annual lake evaporation from pan observations and related meteorological data normally collected in its established observational programs. Since the network of pan stations is quite sparse and the records are notably incomplete, usually seasonal in nature, the development of a universally applicable procedure for extrapolating and interpolating pan evaporation has also been a major objective. This research paper presents the results of these studies, including examples of suggested methods of computing reservoir evaporation, having given selected combinations of basic data.

G. Kullerud (Geophysical Laboratory, Carnegie Institution of Washington, Washington, D. C.) The FeS-ZnS System: A Geological Thermometer--The FeS-ZnS equilibrium diagram has been determined with more than 250 runs, carried out in closed evacuated silica bombs. The relationship between the ZnS α-β inversion temperature and mix-crystal composition has been established. The increase in the ZnS lattice dimensions, when Zn is replaced by Fe, suggests an increase in the ionic character of the mix-crystal bonds with increasing Fe content. At relatively high temperatures equilibrium mix-crystals were obtained by mixing as well as unmixing. Due to exceedingly sluggish reactions below 400° C, points on the equilibrium curves below this temperature were determined by thermodynamic calculations. The influence of pressure upon the FeS solubility in ZnS has been calculated and found to be relatively small. The results were in part checked by experiments. The FeS activity was found to decrease very little from stoichiometric FeS to FeS_2. However, it drops sharply when S is added beyond the amount indicated by the FeS_2 formula. Small amounts of Mn and Cd have little or no influence on the solubility of FeS in ZnS. Thus, the variation in (Fe, Zn)S mix-crystal composition as a function of temperature (and pressure) is known. (Fe, Zn)S mix-crystals formed from sphalerite and iron sulfide are common in nature. Provided sufficient iron sulfide was present the mix-crystal composition reflects the temperature, pressure conditions existing during ore deposition. The temperature of ore formation in a number of deposits has been determined from the composition of this type of mix-crystals.

J. Laurence Kulp and Walter R. Eckelmann (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) The Uranium-Lead Age Studies in the Lake Athabasca Region--A study of a suite of samples of pitchblende, clausthalite and galena from various mines in the Lake Athabasca uranium province has been completed. Isotopic and chemical analyses as well as radon leakage measurements were employed to obtain apparent ages from the various isotopic ratios Pb^{206}/U^{238}, Pb^{207}/U^{235} and Pb^{207}/Pb^{206}. Pb^{210} measurements were used to show that the decay series is now in equilibrium. The apparent isotopic ages range from 220 to 1860 m y. Alteration effects which might explain these anomalies are considered. Uranium leaching and radon leakage are found inadequate to explain the results. The diverse ages can all be calculated on the hypothesis of a single period of pitchblende deposition at 1.90 ± 0.04 b y ago followed by two periods of exsolution of lead at about 1.2 and 0.15 b y. This is consistent with the 207/206 ratio of the radiogenic lead in the clausthalite and galena which apparently formed at the times of recrystallization. However, the existing data do not preclude more than two periods of lead exsolution. This case history helps to define the limitations of the uranium-lead method. It also indicates the usefulness of the anomalies in the ages obtained from lead-uranium isotopic ratios to identify periods of thermal metamorphism.

P. K. Kuroda (Department of Chemistry, University of Arkansas, Fayetteville, Ark.) On the Activity Ratio of the Actinium Series to the Uranium Series Radioactive Elements--The activity ratio of the actinium series to the uranium series radioactive elements obtained from the isotopic constitution of radium (Ra-223/Ra-226) tends to be greater than the well accepted value of R = 0.046. It appears that much better agreements between ages from Pb-206/U-238, Pb-207/U-235 and Pb-207/Pb-206 are obtained, if calculations are made with lead isotopic data and the experimentally-obtained values of Ra-223/Ra-226 ratio, instead of R = 0.046. It was first thought that the high Ra-223/Ra-226 ratio might be due to the non-equilibrium relation between U-238 and Ra-226. However, the results of radiochemical determinations of the ratios of Ra-223/Ra-226, Ra-226/U-238 and U-235/U-238 in a number of uranium minerals indicated that the deviation is greater than expected from the non-equilibrium relation between U-238 and Ra-226.

Arthur H. Lachenbruch (U. S. Geological Survey, Menlo Park, Calif.) Dissipation of the Temperature Effect of Drilling a Well in Arctic Alaska--Temperatures have been measured during a period of 5 1/2 years since drilling of a 3000-ft well through permafrost near Barrow, Alaska. These measurements, which extend to a depth of 595 ft, provide an opportunity to study the dissipation of the ground-temperature disturbance caused by drilling. Comparison of observed temperatures with those computed for various hypothetical distributions of source strength suggests that after 5 1/2 years (on the order of 30 times the duration of the drilling operation) the form of the cooling curve is well approximated by any reasonable assumption of source distribution in time. Equilibrium temperatures computed on the basis of any such assumption agree with one another within about 0.02° C for each depth considered. However, equilibrium temperatures computed from temperature observations made within only a few months of the completion of drilling are quite sensitive to the distribution of source strength assumed. If it is assumed that the ground behaves like an infinite homogeneous medium heated initially by a linear source of finite duration, the equilibrium temperatures computed from the data for the first five months agree within 0.1° C with those computed with data for 5 1/2 years for 21 of the 27 depths considered. The anomalous behavior at the other six depths is believed to result primarily from variation in depth of the physical properties of the rocks.

E. C. LaFond and H. W. Menard (U. S. Navy Electronics Laboratory, San Diego, Calif.) Recent Oceanographic Expeditions Conducted by USNEL--Several oceanographic expeditions have been conducted by USNEL in recent years. Some of these have been for the purpose of supporting underwater acoustic work while the others have been for purely oceanographic research purposes. Navy oceanographic-acoustic ships have been used for most expeditions, while the others have been carried on jointly aboard ships of the Scripps Institution of Oceanography. Expeditions have been conducted in the following areas: Off Central America, Gulf of Alaska, near the Hawaiian Islands, and numerous areas within 1000 miles of San Diego. Repeated expeditions were undertaken in the Bering and Chukchi Seas and Pacific Arctic. These expeditions in the arctic have been conducted every year since 1947, and have been cooperative enterprises with the University of Washington, University of British Columbia, and the Pacific Oceanographic Group. The main objectives of these expeditions are the description of the bathymetric features, vertical water structure, current patterns, water mass distribution, sound scattering layers, and arctic ice character as well as developing hypotheses for explaining the observations.

Paul Lieber and Arthur Farmer (Rensselaer Polytechnic Institute, Troy, N. Y.) On Wave Propagation in Granular Media--Experimental studies relating to the propagation of disturbances in unconsolidated materials encouraged a theoretical investigation suggesting a mechanism governing propagation in such materials. From these theoretical considerations it is inferred that a disturbance imparted to a granular material is propagated in two principal parts. One consists of a wave of small amplitude which anticipates a wave of much higher amplitude propagation at smaller velocity. The first wave is called a precursor and is identified with the elastic deformation of the grains of the unconsolidated material. The second component propagating at a lower velocity and carrying most of the energy imparted by the disturbance is identified with compaction, accomplished by filling the voids between the grains. It was thus inferred that there would be appreciable dissipation of energy associated with the second wave and little attenuation of the precursor wave. Further experiments were conducted to check these conclusions. The results of these experiments show the composite wave structure predicted from theoretical considerations.

Gordon G. Lill (Geophysics Branch, Office of Naval Research, Washington, D. C.) A Tentative Program in Oceanography for the International Geophysical Year 1957-1958--The contents of this paper result from the deliberations of the Technical Panel on Oceanography for the International Geophysical Year. The original brief was prepared by Roger R. Revelle after discussions held at the Woods Hole Oceanographic Institution in June, 1954. The paper has been further modified by the members of the panel. The members are: E. H. Smith, Roger R. Revelle, C. O'D. Iselin, Richard Fleming, Dale Leipper, W. Maurice Ewing, and Gordon G. Lill (Chairman). There will be two major phases to the program. The Island Observatories project, and Operation Deep Current. The Island Observatories project will involve the establishment of approximately 30 new island stations. In the Atlantic these stations are tentatively scheduled for: Iceland, Azores, Canary Islands, Barbados, Ascension, St. Helena, Tristan da Cunha, Cape Verde, South Georgia, and Bermuda. In the Pacific for: Suva, Tahiti, Easter Island, Juan Fernandez, Norfolk, Hawaii, Guam, Wake, Johnston, Point Barrow, Adak, Gulf of Alaska, Queen Charlotte, Ocean Island, Jarvis, Palmyra, Galapagos, Hobart, Invercargill, and MacQuarrie. Three types of sea-level measurements will be involved: (1) measurement of sea level oscillations having periods of 5 to 15 minutes duration; (2) measurement of an oscillation with a period of 3.84 days; and (3) measurement of the long period seasonal changes in sea level. In addition, meteorological observations will be made at all the stations. At Jarvis and Palmyra magnetic measurements will also be made. Operation Deep Current will involve three phases: (1) a study of the deep circulation of the water moving northward from Antarctica into and along the bottom of the Atlantic and Pacific basins; (2) a study of the Equatorial Current Systems in both oceans, and (3) multiple ship surveys in the north central Pacific and north central Atlantic. The details of Operation Deep Current are still under consideration since research vessels from other countries will be participating in parts of the program. The Island Observatories project is well outlined, but still remains to be fully planned in scientific detail and in its international aspects. The entire program is, therefore, tentative and subject to further modification.

William H. Littlewood (U. S. Navy Hydrographic Office, Washington, D. C.) and Frede Hermann (Danmarks Fiskeri-og Havundersøgelser, Copenhagen, Denmark) The Danish Oceanographic and Fisheries Research Vessel Dana, and Its Postwar Program--This paper describes the origin and the present administration of the Danish Ministry of Fisheries' research vessel Dana. The dimensions, the living, working and storage spaces, and the fundamental research equipment are also described. A photograph and plans of the ship are presented. The program of the Dana for the postwar years is briefly reported, including operations in Danish homewaters, the North Sea, the Faeroe Islands area, the North Atlantic and Davis Strait sections, and the Greenland west coast area. Station charts of selected operations are presented in conjunction with the above. Proposed future operations are discussed.

Gerald R. MacCarthy (U. S. Geological Survey, Chapel Hill, N. C.) Natural Earth Potential Anomalies near Point Barrow, Alaska--Studies of some electrical properties of permafrost at the Arctic Research Laboratory, sponsored by the Office of Naval Research and the U. S. Geological Survey, have disclosed an interesting phenomenon. Certain abandoned gravelly beach ridges were found to be markedly negative in natural potential in respect to the surrounding silty tundra during the season of thaw, but became markedly positive during the freeze-up. The magnitude of these potential anomalies can be correlated roughly with the thickness of the active layer and with the rate at which thawing or freezing takes place. These potentials are believed to be caused by the forced circulation of water through the more permeable materials (electro-filtration potential) and perhaps also by the build-up of electrical charges along ice-water interfaces during the freezing process. There is thus some resemblance to the problem involved in porosity determinations in electrical well logging.

William E. Maloney and Raymond J. McGough (U. S. Navy Hydrographic Office, Washington, D. C.) Meteorologically Induced Deviations from Predicted Tide Levels of Chesapeake Bay--Water level fluctuations at Norfolk, Virginia and Baltimore, Maryland are examined for meteorological effects by comparing observed and predicted tide levels. The frequency distribution of observed heights above or below predicted heights are given by months for two years of observations. The effects of meteorological systems on sea level in the Norfolk area are explained, nomograms for predictions are derived, and the accuracy of the technique shown by a comparison of hindcast with observed levels.

Nicholas E. Manos (Tuberculosis Program, Division of Special Health Services, Public Health Service, Washington, D. C.) Tornadoes Spread Disease--Histoplasmosis is a recently discovered disease which is widely prevalent in the Middle West and is sometimes confused with tuberculosis. The causative fungus has been found in the soil, in old buildings, and in other sheltered places, yet its mode of spread has never been demonstrated. The geographic distribution of the disease led to the suspicion that tornadoes might be a means of spread. A check of the records of 160,000 persons tested by the Public Health Service for histoplasmosis against the Weather Bureau records of tornadoes has supported this suspicion. It is inferred from this that the less severe but more frequent storms may be the principal carriers. It is suggested that the tornado, because of its violent and localized effect, might be usable as a natural laboratory for further study of this disease.

William Markowitz (U. S. Naval Observatory, Washington 25, D. C.) Analysis of the Variable Rotation of the Earth for 1951 to 1954--Solutions were made on a homogeneous basis for each of the three years in the interval September 1951 to October 1954. The astronomical observations were made with the photographic zenith tubes at Washington, D. C., and Richmond, Florida, on a total of over 1500 nights. The time determined astronomically was compared with that indicated by two quartz-crystal clocks of high precision of the Bureau of Standards, which had uninterrupted runs. With this much material it was possible to study the variable rotation of the Earth in considerable detail. The amplitude of the one-year term, due apparently to meteorological effects principally, is 30 ms (milliseconds). That of the 0.5-year term, due to the solar tide Ssa, is 10 ms. There were also found two terms of about one ms amplitude each, due to the lunar tides Mf, of period 13.6 days, and Mm, of period 27.6 days. The tides change the moment of inertia of the earth and thereby the rate of rotation. The variation in rotation did not change very much for the three years considered. The variation is well represented by a single expression containing only the annual and semi-annual harmonics. The results derives by Mintz and Munk from meteorological and tidal considerations agree substantially with those found here. The causes of the annual variation in the rotation of the Earth may be considered as being satisfactorily known.

Wilbur Marks and Joseph Chase (Woods Hole Oceanographic Institution, Woods Hole, Mass.) Observation of the Growth and Decay of a Wave Spectrum--In October, 1954, the R. V. ATLANTIS conducted a program of observation of the wind and waves in conjunction with a joint undertaking in wave research designed to obtain the two-dimensional energy spectrum of the sea surface by means of aerial stereo-photography techniques. A series of wave records was made during two periods of high waves. The information obtained from the wave records illustrates the way in which the one-dimensional spectrum (Neumann, 1953) grows and decays, on two separate occasions, in terms of the distributions of energy, wave height and period. Hindcasts are made to verify the wave forecasting method of Pierson, Neumann, and James (1953) for the open oceans, and stress is given to the subjectivity of evaluating the wind parameters from meteorological charts. The results obtained from visual observations, wave records and the prediction technique are compared.

James C. Maxwell (Columbia University, New York 27, N. Y.) The Bifurcation Ratio in Horton's Law of Stream Numbers--Horton's law of stream numbers is modified to apply to stream segments: the numbers of stream segments of different orders in a given drainage basin tend to form an inverse geometric sequence in which the first term is unity and the ratio is the bifurcation ratio. Mathematically:

$$N_o = r_b^{(s-o)} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

or

$$\log N_o = s \log r_b - (\log r_b)o \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where o = order of stream segment, N_o = number of segments of order o, s = largest o, r_b = bifurcation ratio. Plots of log N_o against o appear strikingly linear for nine basins in the San Dimas Experimental Forest, California, and the Appalachian Plateau. Linear regression,

$$\log N_o = a - bo \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

explains 98 pct of the variance of log N_o. Equating corresponding terms of empirical equation (3) with rational equation (2) yields:

$$r_b = \text{antilog } b \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3a)$$

and

$$r_b = \text{antilog } (a/s) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3b)$$

No significant difference is found between solutions (3a) and (3b). Eq. (3a) is recommended as the best empirical expression of bifurcation ratio.

Hugh J. McLellan (Fisheries Research Board of Canada, St. Andrews, N. B., Canada) Major Offshore Projects of the Atlantic Oceanographic Group--The Atlantic Oceanographic Group under the Canadian Joint Committee on Oceanography carries out investigations of the waters off the Canadian Atlantic coast and in the Arctic. A program of seasonal surveys of the Scotian Shelf and Gulf of St. Lawrence has been in operation since 1950. Four times a year a network of 59 stations are occupied in a cruise pattern of some 4000 miles. A number of cruises have been carried out in recent years designed to illuminate features of the Slope Water off the Scotian Shelf and its relation to water conditions on the Banks. The initial cruise of H.M.C.S. *Labrador* in the summer of 1954 circumnavigated North America and occupied 70 hydrographic stations in 20 sections across major channels in the Canadian Archipelago. In the western Arctic this ship worked with the Beaufort Sea Expedition occupying stations in a cooperative program. The program of seasonal cruises is a continuing one. Further Slope Water Surveys are projected and a second Arctic cruise of H.M.C.S. *Labrador* is planned for 1955.

Carroll F. Merriam (Pennsylvania Water and Power Co., Baltimore, Md., retired) Potential Value of Ground Water Data--Programs of observation of the natural fluctuations of ground water covering an extensive area where there is no continuous aquifer are discouraging for the reason that readings must be made for a considerable period of time before they begin to have meaning. The results are not directly translated into quantitative data in the manner that stream flow records are. Consequently to appreciate the potential value of this work it is necessary to have some perspective of the possible future significance. Otherwise opportunities to gather much needed basic hydrologic data may be lost. Papers by the same author describing the method of analysis and the practical application in forecasting assured river flow have appeared in previous *Transactions* of the American Geophysical Union. This paper deals primarily with the precautions believed to be essential in maintaining the high standard of consistency in order to make the effort expended on observation of greatest use in the future. All of the records observed for the Susquehanna after reduction to common scale during the calendar years 1953 and 1954, with the more reliable at the top and the least reliable at the bottom will be shown. In this manner there is the contrast between the excellent results from some wells and the difficulties encountered with others. Without analysis many of these shortcomings would not be apparent.

Arthur R. Miller (Woods Hole Oceanographic Institution, Woods Hole, Mass.) The Effect of Steady Winds on Sea Level at Atlantic City--From a study of tidal records for Atlantic City, New Jersey, and daily weather maps over a period of six months, a nomogram for wind setup as a function of velocity and direction of the geostrophic wind has been developed empirically for the area. With the assumption of 20° for the angle of deviation between surface and gradient winds and allowing for the static effects of barometric pressure, maximum setup is shown when surface wind blows 40° to the right of normal to the coastline. In general, there appears to be a 12-hr lag between the state of sea level and associated winds. These relations are not apparent with local or fast-moving disturbances.

Conrad P. Mook (U. S. Weather Bureau, Forecast Center, Washington, D. C.) A Synoptic Study of the Surface Gusts Associated with the Passage of a Hurricane Overland--A study of the highest gusts of wind associated with the movement of Hurricane Hazel over land on October 15, 1954, reveals an unusual surge of high winds which traveled northward far in advance of the hurricane center. The highest gusts accompanying the passage of the hurricane center are shown to be associated with two lines of convergence one of which is a front. The 1954 hurricane is compared with a hurricane which moved northward and actually increased in intensity over land in 1896 adding evidence by analogy that the maintenance of the energy of Hurricane Hazel over land was partially due to extratropical cyclonic development.

George W. Morey (Geophysical Laboratory, Carnegie Institution of Washington, Washington, D. C.) The Action of Hot Water on Some Feldspars--Liquid water at 350°C and 5000 psi was passed continuously over albite for 34 days, and over microcline for 103 days. The water was collected continuously, weighed, and analyzed. Seventy-eight kg of water was collected from the albite before the run was ended by the exit tube from the bomb being stopped up by analcite, and 194.4 kg of water was passed over the microcline. The amount of material dissolved from the albite amounted to about 316 ppm, and from microcline about 268 ppm. In both cases boehmite was formed, as well as paragonite with albite and muscovite with microcline.

W. H. Munk (Scripps Institution of Oceanography, La Jolla, Calif.) Wind Stress on Water: An Hypothesis--The form drag of wind on an irregular surface is found to equal the product of U^2 (U is anemometer wind speed) and a function of the two-dimensional spectrum of this surface. For a solid surface this function is, of course, independent of U and the form drag is proportional to U^2, as observed over land. Over water, Neumann's frequency spectrum and the glitter measurements by Cox and Munk make this function proportional to U, and hence the form drag proportional to U^3. The computed form drag is not far out of line with measurements by Van Dorn and others. The dependence of form drag on the beam width and frequency spectrum of the surface roughness is discussed. The essential roughness statistics come close to being the mean square slope of the surface, rather than being related to wave height or some other roughness length, as usually assumed. The slope statistics are governed by the high frequency part of the wave spectrum, and this feature accounts for the pronounced reduction of form drag by surface slicks, and the relatively small effect of a limiting fetch. The total drag, $c_1U^2 + c_2U^3$ (skin friction + form drag), must be larger at very high winds than if it followed a U^2 law, as usually assumed.

Frank Neumann (University of Washington, Seattle, Wash.) Sensitivity Controls on Sprengnether Seismographs--In Galitzin type seismograph circuits the sensitivity of the seismograph is controlled primarily by a shunt across the leads between seismometer and galvanometer; but it is also required that the resistance external to the galvanometer be some fixed value for critical galvanometer damping. While an effort is ordinarily made to have the resistance of the seismometer coil equal to the required external resistance of the galvanometer this situation seldom obtains so that the formulas ordinarily found for reducing the sensitivity of the seismograph do not apply. In this investigation formulas are developed for the circuit resistances needed to reduce sensitivity even though the galvanometer CDRX and the seismometer coil are not matched. Certain limitations are revealed. A multiple-circuit device for controlling seismograph sensitivity at the University of Washington is illustrated.

Gerhard Neumann (College of Engineering, New York University, New York, N. Y.) Review of the Present Position and Problems of the Momentum Transfer across the Air-Sea Interface--The various attempts to estimate the total wind stress at the sea surface are briefly reviewed and the difficulties in the application of the methods used in the past are discussed. Probable relationships between the state of the sea surface and the results obtained under different conditions in the open sea and in wind tunnel experiments are pointed out and suggestions made for future field work.

Gerhard Neumann (College of Engineering, New York University, New York, N. Y.) On Wind-Generated Wave Motion at Subsurface Levels--The characteristics of ocean waves at subsurface levels are derived on the basis of wave spectra as a function of the depth. It is shown that the decrease of total wave energy of the composite wave motion with depth is much less than it would be expected for an 'equivalent wave' (significant wave) of the same energy at the sea surface. The average 'period,' the period of the most energetic wave component, the water displacements and accelerations below the sea surface are given as functions of the depth z and the wind velocity v. These wave properties change considerably with increasing depth as a result of the different attenuation of the individual wave components in the spectra. The introduction of a dimensionless parameter, gz/v^2, where g is the acceleration of gravity, simplifies the graphical representation of the derived relationships, and their practical application for determining the motion of submerged bodies.

Marcus H. Norwood and Edwin J. Chernosky (Geophysics Research Directorate, Air Force Cambridge Research Center, Cambridge, Mass.) A Numerical Geomagnetic Flux and Activity Recording System--An instrument which is intended for use as a recording fluxmeter and as a recording activity indicator has been developed and partially evaluated at the Air Force Geophysics Research Directorate. Its purpose is to mechanize geomagnetic data reduction and to provide additional information. This instrument is a self-balancing potentiometer strip-chart recorder modified to include a mechanical integrator. The integrator generates pulses at a rate which is proportional to the input signal level to the potentiometer. A printing counter is used to count the pulses and to print their totals at selected unit time intervals. These totals are proportional to areas. If a signal proportional to the magnetic field vector is connected to the instrument the integrated area per unit time represents the average magnetic vector for that interval. When positive and negative areas under the derivative functions are counted separately and added arithmetically the totals are expected to be a useful measure of the magnetic activity (variability) in each time interval.

Charles B. Officer (Woods Hole Oceanographic Institution, Woods Hole, Mass.) Cruise of the Research Vessels Atlantis and Caryn to the Caribbean, January-March, 1955--Seismic determinations were made of the thickness of the sediments and the depth of the bedrock in the eastern Caribbean between Trinidad and the Virgin Islands. Simultaneously, extensive studies were made of the fertility and productivity of the overlying waters, and an acoustically-guided camera was used to photograph organisms in the scattering layer.

Donald E. Outlaw and Edward C. Rhodehamel (Ground Water Branch, U. S. Geological Survey, Trenton, N. J.) Pine Barrens Research Project, New Jersey--The U. S. Geological Survey, in cooperation with the New Jersey State Department of Conservation and Economic Development, and Rutgers University, is conducting hydrologic research in the Pine Barrens region of New Jersey. The project was begun in 1951, and it should be continued for at least 30 years. The primary purpose of the program is to learn as much as possible about the hydrology and water-yielding potentialities of this 2000 sq mi region, about one-fourth of the State. Also, an effort will be made to evaluate the effects of changes in forest cover produced by forest-management techniques upon the total yield and seasonal availability of water. The hydrologic factors will be studied by the U. S. Geological Survey, and the changes in overall vegetative cover will be evaluated by Rutgers University (Department of Botany). The silviculture will be planned and executed by the foresters of the Department of Conservation and Economic Development and of the U. S. Forest Experiment Station. The program is centered primarily on an area in Lebanon State Forest containing two small watersheds. After a period of instrumentation and calibration, the vegetation on one of these watersheds will be converted from a predominantly oak forest to a predominantly pine forest, and the other will be maintained as a control. Instrumentation will include networks of observation wells, rain gages, interception stations (both for vegetation and for litter), soil-moisture stations, climatic and evaporation stations, and two stream-gaging stations. Instrumentation completed includes the two stream-gaging stations and parts of the rain-gage and observation-well networks. It is hoped to complete the remainder of the instrumentation in two or three years. Preliminary evaluations of the vegetative cover and of the near-surface geology in the two watersheds have been completed, and reports on these two phases of the project are in preparation.

Samuel D. Owen (Det. 1, 1370th Photo-Mapping Group, Orlando AFB, Florida) Net Design for Hiran Surveys--Problems involved in the design of nets for Hiran surveys are set forth. Factors are suggested which may be used in the development of a criterion for classification of trilateration as to order of accuracy. A method for computing the strength of figure of a trilateration net and an interim accuracy criterion for planning nets for first-order surveys are proposed. The methods and procedures currently used by personnel of the 1370th Photo-Mapping Group in net design are discussed.

H. L. Penman (Rothamsted Experimental Station, Harpenden, Herts., England) Estimating Evaporation--Evaporation is a physical process that must satisfy two basic requirements. There must be an energy supply to provide heat of vaporization; and there must be some transport mechanism for removing the vapor. Combining these concepts it is possible to derive an expression for evaporation rate that depends only on measurable weather elements. By making some simplifying approximations the weather data needed reduce to: duration of bright sunshine, air temperature, air humidity and wind speed. The quantity obtained is E_O, the evaporation rate from a hypothetical open water surface exposed to the measured weather. Formally, and empirically, it is possible to convert E_O into E_T, the potential transpiration rate from a short green crop cover, completely shading the ground and never short of water. This computation has formed the basis of successful experiments in irrigation control; and, with reasonable empirical modification to allow for conditions when water supply becomes a limiting factor, has been applied with some success in studies of the water balance of catchment areas.

Helen B. Pettit and Edward Manring (Air Force Cambridge Research Center, Cambridge, Mass.) Intensity Variations of [OI] 5577 and Sodium D in the Nightglow--From August 1953 to January 1955 an automatic photoelectric photometer has been in operation at Upper Air Research Observatory, Sacramento Peak, Sunspot, New Mexico (lat. 32°47'N, long. 105°48'W and elevation 9250 ft). Observations were made of [OI] 5577 and sodium D in the nightglow. The results of this study show: (1) The diurnal variation in intensity of [OI] 5577 takes three forms. About 54 pct of the nights have a maximum near midnight as normally observed by stations in mid-latitudes, 36 pct have a minimum near midnight as reported in the lower latitudes, and 10 pct have no appreciable fluctuation during the night. This seems to indicate that this latitude may represent a lower limit to a possible geographical zone of nightglow maximum. (2) The sodium D observations at this station are remarkably similar to others made in mid-latitudes. (3) In comparing simultaneous observations made at two stations of different longitudes it is found that the average absolute intensities are much the same, but the diurnal variations are dissimilar in detail.

B. B. Phillips, P. A. Allee, J. C. Pales, and R. H. Woessner (U. S. Weather Bureau, Washington, D. C.) An Experimental Analysis of the Effect of Air Pollution on the Conductivity and Ion Balance of the Atmosphere--A series of conductivity measurements made in a large sealed sphere has shown that in ordinary outside air or polluted air the negative electrical conductivity approximates the value of the positive conductivity. Equal conductivities are normally associated with an excess in the density of the small positive ion. It is found that with decreasing pollution the value of the negative conductivity increases more than does the positive and the ionic densities then approach equality. In clean air, equal densities of the positive and negative light ions are observed, and the conductivities become proportional to the commonly accepted laboratory values for the ionic mobilities. The results are consistent with recently developed expressions for the diffusion of ions onto atmospheric particles.

Fred B. Phleger (Scripps Institution of Oceanography, La Jolla, Calif.) Results of the Swedish Deep-Sea Expedition--The Swedish Deep-Sea Expedition was the first major oceanographic expedition of the post-war period. Deep-sea cores and a variety of oceanographic observations were made in tropical areas of all major oceans. This expedition is noteworthy for the thoroughness and relative speed with which the field results have been interpreted and made available and the laboratory studies have been pursued. Important contributions have been made in several aspects of deep-sea research, such as chemistry and chronology in eastern Pacific sediments, faunal sequences in Atlantic sediments, particle distribution in sea water over the deep basins, microtopography of deep-sea areas, thickness of basin sediments, studies of the interrelations of radioactive materials in marine sediments, and oceanography of the Equatorial Counter Current.

G. L. Pickard (University of British Columbia, Vancouver, B. C., Canada) British Columbia Inlets--Commencing in 1951, cruises have been made by the Institute of Oceanography, University of British Columbia, in the majority of the inlets of the British Columbia mainland coast and of the Queen Charlotte Islands. The object was first to describe the general oceanographic conditions in these waters, and secondly to pick out for further study those features which are characteristic of the region. Observations were made of salinity, temperature, oxygen, bottom material and plankton. The 1951 cruise demonstrated the estuarial character of the inlets, most of which are fed by large rivers. The subsequent surveys were intended to give an estimate of the extent of annual variation. Recently, studies of the velocity profiles have been commenced, and measurements made of internal waves in certain of the inlets.

William H. Pinson, Jr., Milo M. Backus, and Leonard F. Herzog (Nuclear Geophysics Section, Department of Geology and Geophysics, Massachusetts Institute of Technology, Cambridge, Mass.) The Rb and Sr Content and Geologic Age of Certain Lepidolites, and Their Radiogenic Ca^{40} Content--The Rb and Sr content and Sr isotope composition of several lepidolites has been determined by the mass spectrometric isotope dilution technique. Two of the samples, Bikita Quarry, So. Rhodesia, and Pala, California, are from the international interlaboratory calibration suite recently distributed by this group. Our results for the Bikita sample are in excellent agreement with the independent analysis of Nicolaysen, Aldrich, and Doak. Radiogenic Ca^{40} has been determined in the same lepidolite. These results are discussed and techniques summarized.

Arie Poldervaart (Columbia University, New York 27, N. Y.) Zircons in the Granite Series--Most zircons in arenites are rounded and have elongations < 2.0. In finer grained sediments zircons are also smaller while proportions of broken grains increase. Lutites contain more zirconium than can be accounted for by zircon. Zirconium in basalts is partly in the pyroxene lattice, partly in zircon. These zircons are irregular chips and are of late crystallization. Most zircons of intrusive granites and diorites are euhedral and of early crystallization. Elongations are generally

>2.0 but may fall below 2.0. Zircons in a pluton are the same in the same rock type but may differ in different rock types. Zircons of comagmatic intrusives and extrusives are the same. Zircons in arenites do not recrystallize during regional metamorphism even in the sillimanite grade, nor in contact aureoles of granitic plutons. In fused glasses zircons show clear signs of resorbtion. In autochthonous granites formed from arenites zircons may remain unchanged or acquire subhedral shells around original rounded cores. Shell growth and eventual disappearance of distinct cores produces euhedral zircons, generally with elongations < 3.0. Some granitic plutons have zircons with elongations up to 32.0. This problem is being studied.

Frank Press and Maurice Ewing (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) Maximum Group Velocity of Rayleigh Waves between 60 and 80 Seconds--In the period range 15-60 sec crustal Rayleigh waves show an increase of velocity with period. As the period increases between 80 and 225 sec, mantle Rayleigh waves decrease in velocity. The maximum value of group velocity found by combining both dispersion curves is about 3.9 km/sec and falls between 60 and 80 sec. Neglect of the mantle velocity gradient in interpretation of crustal Rayleigh waves leads to a value of mantle shear velocity which is too small. The effect of the maximum group velocity on the initiation of crustal Rayleigh waves is illustrated with seismograms.

D. W. Pritchard (Chesapeake Bay Institute, Johns Hopkins University, Annapolis, Md.) Contribution of Longitudinal Variations in Strength of Tidal Current to the Maintenance of a Mean Surface Slope in an Embayment--It is shown that the mean equations of motion applicable to a tidal embayment or estuary contain an acceleration term of the type $(1/2)\partial U_0^2/\partial x_1$, where U_0 is the tidal current amplitude and x_1 is the longitudinal coordinate. The rate of change of tidal current strength along the length of the embayment is thus capable of balancing a portion of the mean surface slope of the embayment. If the tidal current amplitude decreases from the mouth towards the head of the embayment, a mean upward slope of the water surface from the mouth towards the head can be maintained. Theoretical calculations are compared to observed slopes in a special tidal model flume maintained by the Waterways Experiment Station, U. S. Army Corps of Engineers, Vicksburg, Mississippi.

Hans Ramberg (University of Chicago, Chicago, Ill.) A Study of Boudinage Structures--Examples on boudinage and pinch-and-swell structures are described and the mechanisms of formation discussed. One dimensional plastic compression and compensating one or two dimensional expansion of layered cakes of putty, plasticene and cheese results in structures strikingly similar to the natural boudinage and pinch-and-swell structure. Studies of the boudinage and related structures give informations about relative plasticity and relative strength of rocks. The commonness of boudinage structures in gneiss-crystalline schist regions show that one dimensional compression and compensating elongation in other dimensions is a very common mode of deforming crystalline rocks. The tension which this kind of plastic flowage creates in competent rock layers does not only produce boudinage or pinch-and-swell structure, but is also important in localizing growth of mineral during metasomatism. Mathematical analysis of the boudinage evolution shows that field measurements combined with data for tensile strength of rocks and their viscosity are sufficient to estimate pressure gradients and rate of flowage connected with formation of boudins.

A. C. Redfield and A. R. Miller (Woods Hole Oceanographic Institution, Woods Hole, Mass.) Water Levels Accompanying East Coast Hurricanes--Tide records from Bermuda indicate that hurricanes while over the deep sea are accompanied by an elevation of the sea surface just about sufficient to compensate for the reduced barometer pressure; that is, less than two feet. Along the open coast of the eastern States hurricanes produce much greater increases in sea level of two sorts: (1) Along the coast parallel to the storm track, a gradual rise in level begins long in advance of the passage of the center, and is attributable to the easterly winds which precede the storm. This effect is trivial along coasts normal to the storm track. (2) A surge of short duration at the time the center crosses the coast. The amplitude is maximal between 50 and 100 mi east of the center and is in excess of eight feet. The development of the surge appears to depend on the limited depth of the continental shelf.

Important effects are due to local coastal topography. The amplitude of the surge is greatly augmented in embayments open to the south such as Narragansett and Buzzards Bays. The surge in Block Island Sound gives rise to a solitary wave which advances westward along Long Island Sound and reaches New York some four hours later. With the passage of the storm the wind-shift releases water impounded along westerly coasts and gives rise to sudden resurgences, such as that which inundates the eastern coast of Buzzards Bay. Off the New Jersey coast they take the form of oscillations of the sea level with a period of five to seven hours.

Robert O. Reid (Department of Oceanography, Texas College, Texas) Hurricanes: Their Storm-Tide Potential, Wave-Energy Index, and Probability--This paper deals with four important questions intimately related to the problem of evaluation of risk for coastal installations which are vulnerable to attack by waves accompanying high water levels due to hurricanes. These questions are: (1) What is the frequency of recurrence of any hurricane for a given length of coastline near the site in question? (2) What parameter (or set of parameters) is to be selected as an optimum index for the purpose of tagging different hurricanes in respect to their gross intensity? (3) What per cent of the hurricanes in (1) are at a specific level of intensity (or greater) as defined by the answer to (2)? (4) Over what length of coastline could the hurricane center pass and still give storm tides and waves at or near (say within five per cent of) the maximum value for that hurricane? The answers to (1) and (3) depend upon the hurricane statistics for the locality concerned. Some results are given for the northwestern Gulf Coast region of the United States. The answers to (2) and (4) can be had only after a complete understanding of the air to sea momentum transfer and hydrodynamic behavior of the water under different conditions of bottom topography, coastal configuration, storm size, intensity and speed or propagation is achieved. Present knowledge of storm tides and waves suggests at least an approximate means of classification of hurricanes in respect to their capacity for producing these phenomena. Two indices (storm-tide potential and wave energy index) are offered in this paper for such classification. These are based upon three readily measurable quantities: central pressure anomaly, radius of the zone of maximum winds, and the mean slope of the continental shelf. Application of these indices to the hurricane data of the United States since 1900 indicates that the logarithms of these indices possess nearly Gaussian distribution. This affords an approximate means of evaluating the probability of recurrence of storms having a given level of wave energy index or storm-tide potential for a particular site.

R. Revelle, G. Arrhenius, T. Cromwell, R. Fisher, E. Goldberg, R. Holmes, J. Isaacs, H. Menard, J. McGowan, R. Raitt, and W. Wooster (Scripps Institution of Oceanography, La Jolla, Calif. and U. S. Navy Electronics Laboratory, San Diego, Calif.) Scripps Deep Sea Expeditions, 1950-1954--During 1950-1954, the Research Vessels Horizon and Spencer F. Baird, of the Scripps Institution of Oceanography, carried out, in part in cooperation with the U. S. Navy Electronics Laboratory, eight exploring expeditions into the deep Pacific. On these voyages the two ships traveled 128,000 miles, and each was at sea more than a year. They ranged from Kamchatka and the southern part of the Bering Sea on the north to the Tropic of Capricorn on the south, and from the coasts of the Americas on the east to Japan and the Marshall and Fiji Islands on the west. The central objective was to make a reconnaissance survey of the characteristics of the waters, the depths and sediments of the sea floor, the structure and forces within the Earth's interior beneath the sea floor, and the marine life of the Pacific. The use of modern tools for oceanographic research was emphasized, although the familiar methods of investigating the water and contained organisms were also employed on a large scale. Many of the data obtained are still being worked up and the materials collected are still being analyzed. Some of the results have been published or submitted for publication and these are briefly summarized.

R. M. Richardson (Ground Water Branch, U. S. Geological Survey, Memphis, Tenn.) Tidal Fluctuations of Water Level Observed in Wells in East Tennessee--Semidiurnal water-level fluctuations of tidal period have been observed in wells completed in the Chickamauga limestone of Middle Ordovician age in east Tennessee. The periodic oscillations of the water level are similar to fluctuations in artesian pressure that in other localities have been recognized and correlated with Earth tides.

Irwin Roman (U. S. Geological Survey, Washington, D. C.) The Apparent Resistivity of a Single Uniform Overburden--The problem of the distribution of potential over a space divided into three regions by two parallel planes is formulated and solved by the method of images for the case in which the pole lies between the two planes and for the case in which it lies in an external region. For the geophysical case of a single uniform overburden with horizontal plane faces and with the upper medium a perfect insulator, the solution is reduced to forms permitting numerical evaluation with considerable accuracy. The direct solution is expressed by an infinite series. For small displacements, local expansions are developed and for large displacements, asymptotic expansions are developed. The theoretical formulas are reduced to eight-decimal tables of a modified potential function and the application of these tables to specific problems is illustrated by a discussion of the superposition method for interpreting observations made with the Wenner or Lee partitioning method.

Elizabeth Rona, L. O. Gilpatrick, and Lela M. Jeffrey (Oak Ridge Institute of Nuclear Studies, Oak Ridge, Tenn.) Uranium Analysis of Sea Water by Isotopic Dilution--The isotopic dilution method of analysis was used to determine the uranium content of various sea waters. Uranium was concentrated by means of solvent extraction from two to three liters of sea water. The uranium was analyzed by mounting it on a tantalum filament in the form of the nitrate, and examining the UO_2^+ ions in a Nier-type 60° mass spectrometer. The results indicate a value of about 3.3×10^{-9} g of U/g of sea water for the waters of the Gulf of Mexico and the North Atlantic Ocean.

M. I. Rorabaugh (Ground Water Branch, U. S. Geological Survey, Tallahassee, Fla.) Prediction of Ground-Water Levels on Basis of Rainfall and Temperature Correlations--A method for predicting ground-water levels in the glacial-outwash deposits in the Ohio River valley near Louisville involves development of curves by graphical correlation to define the effects of winter precipitation and winter temperature on recharge to the water table, and to determine the decline in the water table as water leaks to the Ohio River. Recharge occurs in the winter when evaporation and transpiration are at a minimum and when the soil is at or near field capacity. Several months is required for the water to percolate through about 60 ft of alluvium and reach the water table.

John C. Rose and G. P. Woollard (University of Wisconsin, Madison, Wisc.) Results with the Gulf Pendulums over the North American Gravity Standardization Range--Results are given for a series of gravity measurements carried out with three different sets of compound quartz gravity pendulums of the Gulf Research and Development Co. between Paso Cortez, Mexico, D. F., and Fairbanks, Alaska. The program described includes a series of 30 sets of observations made in 1951 with one set of pendulums, and a second series of 45 sets of measurements made with each of the two other sets of pendulum equipment in 1953. Comparative results obtained for repeat observations indicate agreement on the latter measurements to better than ± 0.5 mgal. Allowance for two tares in the earlier measurements as revealed by both gravimeter measurements and the later pendulum observations gives a similar overall degree of accuracy for the 1951 series.

Clarence S. Ross, I. Friedman, and Robert L. Smith (U. S. Geological Survey, Washington 25, D. C.) The Origins of Water in Glassy Rocks as Determined from the Isotopic Composition--The amount and hydrogen isotopic composition of water extracted by melting glassy rocks was determined. Perlite commonly contained about 3.5 pct water, whereas the obsidian-like pellets enclosed in perlite contained about 0.3 pct water. The water in the perlite differs in isotopic composition from that in the obsidian pellets. This difference, plus the fact that perlite from different geographical areas contains water whose isotopic composition approximates that of the meteoric water of the region lends weight to the hypothesis that most of this water is of secondary origin. In contrast the water in the obsidianlike pellets (approximately 0.3 pct water) is probably magmatic in the sense that it was present during the time that the glass was molten. This difference between the water in the perlite and that included in the obsidian pellets correlates with differences in optical properties of the glasses.

R. D. Russell and G. L. Cumming (University of Toronto, Toronto, Canada) Lead Isotope Abundances--One of the more remarkable features of common lead isotope abundances is the simple manner in which they appear to be related to the age of the mineral from which the lead is extracted. This relationship, expressed in various forms, has been used by different authors to estimate ages of lead ores. It is usual to obtain these 'galena' ages from curves based on such formulas as

$$Pb^{206}/Pb^{204} = (Pb^{206}/Pb^{204})_o + (U^{238}/Pb^{204})\,(e^{\lambda t_o} - e^{\lambda t}),$$

or in the form

$$\frac{Pb^{207}/Pb^{204} - (Pb^{207}/Pb^{204})_o}{Pb^{206}/Pb^{204} - (Pb^{206}/Pb^{204})_o} = \frac{1}{137.8}\,\frac{(e^{\lambda 1 t_o} - e^{\lambda 1 t})}{(e^{\lambda t_o} - e^{\lambda t})}$$

The parameters in these equations are usually determined by assuming some knowledge of the age of certain lead minerals. Alternatively, abundance-time curves which also give apparently reasonable ages can be obtained in a manner which does not assume the explicit form of the equations above and which required no dated lead minerals. This procedure will be described and some typical results quoted. In the development of abundance-time curves it is found that the above equations, when used to represent the abundance of average lead ores, lead to small, systematic discrepancies between observed and calculated Pb^{206}/Pb^{204} and Pb^{207}/Pb^{204} ratios. This effect will be discussed and possible reasons given.

Yasukazu Saito (Department of Oceanography, Texas A and M College, College Station, Texas) The Theory of the Transient State Concerning Upwelling and Coastal Current--In the Gulf of Mexico and the California coastline the phenomenon of upwelling occurs by the influence of prevailing wind and is largely a matter of transient state. As an extension of the theoretical treatment (for steady state) which was made by Hidaka (1954), the manner in which the upwelling and coastal currents gradually develop in an ocean initially at rest is derived for the case where the wind suddenly begins to blow over the sea surface.

Ira T. Sanders (U. S. Coast and Geodetic Survey, Washington, D. C.) Recent Oceanographic Activities of the U. S. Coast and Geodetic Survey--This Bureau conducts oceanographic observations and sampling as part of the normal routine during hydrographic operations, whether they be for new or revision surveys. Over the years sufficient equipment of the prevailing standard types had been procured to meet our requirements. In 1952, however, it was realized that most of this equipment was out of date and not capable of producing results required in modern oceanographic evaluations. At that time a program of procurement, on a modest scale, was inaugurated. As a result, five of our major vessels have now been equipped with modern oceanographic gear, including oceanographic winches, or old type equipment has been modified for present day requirements. Since the installation of new equipment, routine bathythermograph observations have been made while on sounding lines by all vessels operating in the Aleutian Islands Area, the Bering Sea, the Gulf of Mexico, and the Straits of Florida. Oceanographic observations at numerous stations in those areas have also been made in accordance with procedures outlined in H. O. Pub. 607, except that no determinations of dissolved oxygen were made. Special studies of surface currents were made in the Gulf of Mexico and the Straits of Florida by the 'set and drift' method employing EPI. Additional current observations have been conducted in the vicinities of St. Lawrence and Kanaga Islands in Alâska. Several interesting new sea mounts have been discovered and developed in the Gulf of Alaska.

Murray H. Schefer (U. S. Navy Hydrographic Office, Washington, D. C.) Work of the Oceanographic Survey Unit--During the period 1949-1953 the Oceanographic Survey Unit conducted extensive investigations in the North Atlantic. Data from approximately 1200 standard oceanographic stations were collected. Especially noteworthy was an anchor station which was occupied for 27 consecutive days during June-July, 1953. This station was revisited for two days during April, 1954.

Leonard Schiff (Division of Irrigation, Soil Conservation Service, Bakersfield, Calif.) The Status of Water Spreading for Ground-Water Replenishment--Methods of spreading water on land surfaces and by injection are reviewed and some results given. Some localities utilizing or contemplating the use of water spreading to replenish ground-water supplies are mentioned. Included are: (1) developments in vegetative, chemical and mechanical treatments to increase infiltration rate; (2) shaft, trench, and pit injection methods which cut through less pervious soil and inject water into aquifers; and (3) operational procedures such as cultural methods, length of wetting and drying periods, and surface head. Soil-water movements are described and interpreted in the light of the Darcy equation. Limitations in the use of treatments based on the surface soil and stratigraphy are described. Solutions to some problems and research directed toward existing needs are mentioned. A strip system and rotational system of spreading water based on an infiltration rate-percolation rate ratio are described. The strip system uses portions of an area and it is conceived that as much water may infiltrate as using the entire area. Surface soil treatment to increase this ratio may result in additional benefits. Land between flooded portions might be farmed or used for other purposes. This system visualizes a 'subsurface lake.' In the rotation system some portions will be flooded while infiltration rates remain high and other portions will be drying for recovery in infiltration rate. Tools to determine the suitability and characteristics of a proposed spreading area, such as soil surveys, laboratory tests of water and soil, well logs, jetting, cable tool test holes and infiltrometers are discussed. Examples are given of water spreading grounds constructed on sites selected by the use of these tools.

Allen Schooley (Naval Research Laboratory, Washington 25, D. C.) Facet Separation Distributions of Wind-Created Water Waves--Optical measurements made using a small water-wind tunnel, having a maximum fetch of 26 inches, indicates that the median distance between the facets of the surface in the direction of the wind, is approximately 0.14 inch for wind velocities between 11 and 22 knots. In this range the first quartile of the distribution is about 0.09 inch and the third quartile is about 0.25 inch. Below 11 knots the median separation between the facets increases rapidly.

Harry E. Schwarz (Washington District, Corps of Engineers, Washington, D. C.) Flood Volume Frequency Estimates--The planning and design of many flood control and water utilization projects are affected not only by the frequency of peak flows but also by the frequency of stream flow volumes for various given durations. To study these volume-frequency relationships, 108 basins with long records distributed throughout the United States were selected and the maximum annual peaks, the 1, 3, 10, 30, and 90 day volumes and the annual runoff volume were tabulated. Based on procedures prepared by L. R. Beard, frequency curves were prepared for each station and each duration, by computing the means, the standard deviation, and the skew coefficient. An analyses of these computed statistics showed that the Pearsons Type III function can be taken for the characteristic function of the volume-frequency relationship and that the skew coefficient can be taken as a function of duration only. An example shows the development of volume-frequency-duration curves for a gaged watershed and its use in determining flood storage requirements.

Robert P. Sharp (California Institute of Technology, Pasadena, Calif.) The Behavior of Ice in Glaciers--Glaciers largely at the pressure-melting temperature were studied. Primary (sedimentary) features inherited from accumulated snow are gradually obscured by secondary (metamorphic) structures, especially foliation, developed during glacier flow. Crystal growth and recrystallization are accompanied by development of strong patterns of preferred orientation (Rigsby). Explanation in terms of basal gliding in ice crystals is difficult, but the patterns are known only from surface ice and may be due to recrystallization following flow. Measurements on Saskatchewan Glacier, Canada (Meier), confirm Reid's deductions that a steady-state valley glacier in a uniform channel has maximum velocity at the firn limit and that the directions of flow above and below that limit are respectively obliquely dawnward and obliquely upward. A 1000-foot bore hole in Malaspina Glacier, Alaska, gives no support to Demorest's concept of extrusion flow. Bore holes record slight flowage of ice within the 'brittle crust' of both Malaspina and Saskatchewan glaciers in two to three years at shear stresses as low as 0.01 kg/cm^2. The tendency is to regard ice as a quasi-plastic substance, but in parts of some glaciers at the pressure-melting temperature it may approach a quasi-viscous substance in behavior.

Leon Sherman and Noel E. LaSeur (Florida State University, Tallahassee, Fla.) Observational Requirements of Tropical Meteorology--The observational requirements in meteorology may be divided along several lines: operation versus research, quantity or quality, existing versus new facilities. The current tropical meteorological networks, exemplified by that of the Marshall Islands area during bomb tests or by the Caribbean are so sparse as to make just possible the gross analysis of moderate to strong disturbances of several hundred miles or larger diameter. At least in the Caribbean, they could be much improved by the addition of reports from the many surface ships and aircraft in the area which do not now report. Because of the nature of ship and aircraft reports, the pressures are less likely to be measured to the accuracy required for the tropics than are the winds and weather; accordingly emphasis should be put upon the latter in any extension of the reporting ship and aircraft list. Extension of weather reconnaissance activities and a spreading of the upper-air station network are essential in areas (like the Caribbean) which affect the forecast for regions of United States responsibility. For the purpose of fixing upon synoptic models for the tropics (including their life histories and propagation) short periods of very intensive aerial reconnaissance involving closely spaced flights over each track are almost a necessity. Multiple aircraft flights into a hurricane will be needed if even a semi-quantitative mapping of such a storm is to be accomplished. The use of new techniques such as that of constant level balloons should be explored; the existing codes for reporting cloud and convective activity are virtually useless and should be modified.

Masao Shiotani (Department of Oceanography, Texas A and M College, College Station, Texas) and Hideo Arai (Railway Technical Research Institute, Tokyo, Japan) Snowdrift Control by Shelterbelts--In this paper the authors investigate the manner in which a shelterbelt controls the drifting of snow. After a brief discussion of the snowstorm, the vertical distribution of snow in the fully developed snowstorm and the generation of snowdrifts, the effect on the control of snow of four vegetational factors of the shelterbelt are investigated. These factors are height, breadth, height to the crown base and density of the belt. In addition to wind-tunnel work, field experiments were undertaken on two different shelterbelts (one a snowstorm protection shelterbelt of the Japanese National Railways; the other an artificially made forest). Results are expressed as the decrease of the wind velocity, both in the windward and the vertical direction, total deposit of snow, accumulation of snow after a snowstorm and drifting snow both in the interior and around the forest. The authors further discuss the safety of the road and railway on the leeward wide of the shelterbelt from the viewpoint of the protection from the snowstorm.

Sam Shulits, C. D. Sims, Jr., and D. J. Stull (Pennsylvania State University, University Park, Pa.) The Dilemma of Bed-Load Formulas--About a dozen bed-load formulas exist, with no general acceptance of the most serviceable one or ones in the manner that the Manning formula is accepted and used for open-channel flow. Various formulas are said to result in discrepancies of 1000 pct; yet six of them are found to fit the same flume data equally well. The initial results of comparative investigations of this anomalous situation are presented in this paper.

E. N. Silverman and T. F. Bates (Pennsylvania State University, University Park, Pa.) X-Ray Diffraction Study of Orientation in the Chattanooga Shale--The use of x-ray diffraction and statistical analysis has resulted in a technique for obtaining a quantitative measure of orientation in fine-grained sediments. The orientation distribution of a sample is obtained by utilizing a recording spectrometer fitted with a rotating sample holder. The intensity distribution is then analyzed using a modification of the chi-square statistic. The proposed measure of orientation is called orientation index and is expressed as: $OI = \chi^2/A$, where χ^2 equals the sum of the squared deviations between the observed and the theoretical, divided by the theoretical and A equals the area under the intensity distribution. The technique was used to study the orientation of the illite and mica in 58 samples taken from a drill core of Chattanooga shale in order to determine whether there is any evidence of textural control of the uranium in the formation. Statistical analysis of the data derived from these samples has shown that: (1) the orientation indices are normally distributed, (2) on the basis of the orientation of illite and mica no significant differences exist between stratigraphic units, and (3) from the standpoint of orientation as measured here, there is no association between texture and uranium in the drill core of Chattanooga shale that was investigated.

R. H. Simpson (U. S. Weather Bureau, Washington 25, D. C.) Plans for Research for the Hurricane Inundation Problem--Most loss of life from hurricanes is from high water, not winds. For this reason the Weather Bureau proposes to conduct an intensive investigation of storm surges and tidal effects resulting from hurricanes. Plans include the establishing of a number of well equipped oceanographic stations and the organization of disaster survey teams to move into coastal areas in the wake of hurricanes for the purpose of collecting detailed information concerning distribution and rate of rise of high water. Various studies will be concerned not only with analyses of these data, but also with theoretical models for storm surges, and with synoptic weather types leading to major inundations.

F. G. Walton Smith and Ilmo Hela (Marine Laboratory, University of Miami, Coral Gables, Fla.) Oceanographic Work of the Marine Laboratory, Miami--Offshore studies during the past year consisted of a hydrographic-acoustical cruise to the Caribbean Sea; a hydrographic cruise to the Santaren Channel, Nicholas Channel, and Straits of Florida; and routine hydrographic studies in the Straits of Florida and Old Bahama Channel. The Marine Laboratory has taken possession of the M/V Gerda, which is ideally suited for major offshore cruises; final scope of plans for employing Gerda for hydrographic studies will depend upon additional funds. A large-scale investigation of the continuous changes in the total heat and water transport by the Florida Current has been prepared.

J. R. Smith and H. S. Yoder, Jr. (Geophysical Laboratory, Carnegie Institution of Washington, Washington, D. C.) Variations in X-Ray Powder Diffraction Patterns of Plagioclases--The differences between the 2θ angles (Δ2θ) in four pairs of peaks in Geiger counter-diffractometer patterns of 53 chemically analysed plagioclases and 15 synthetic plagioclases have been measured. The variation of Δ2θ with composition is uniquely defined for synthetic plagioclases crystallized in the dry way, for andesines, labradorites and bytownites from thick stratiform mafic intrusions, and possibly for albites and oligoclases from pegmatites. The curves for the natural plagioclases and for the dry synthetic plagioclases differ markedly in the composition range An_0 to An_{80}, but appear to coincide from An_{80} to An_{100}. Values intermediate between the curves for the dry synthetic plagioclases and for the natural plagioclases from pegmatites and stratiform mafic intrusions were obtained in four plagioclases from anorthosites and ten from volcanic rocks, suggesting that these plagioclases may have structures intermediate between those of the dry synthetic plagioclases stable at high temperatures and those of the plagioclases from stratiform mafic intrusions, pegmatites and granites stable at relatively low temperatures. Intermediate values were also obtained for five albites and oligoclases synthesized under extreme water pressures, suggesting that it may be possible to synthesize the modifications of sodic plagioclases which are stable at low temperatures. In the present state of knowledge, measurements of Δ2θ cannot be used to determine the composition of a plagioclase. As pointed out by previous workers, such measurements offer a means of detecting structural transitions between 'high-temperature' and 'low-temperature' forms if the composition of the sample is known.

R. J. Smith (Louisiana State University, Baton Rouge, La.) Gravity Cross Section of the Venezuelan Coast Ranges--Forty-four gravity stations were established across the metamorphic rocks of the Coast Ranges of Venezuela from La Guaira on the north, through Caracas, and south to the unmetamorphosed sediments at Ortiz. The readings were taken on a Worden meter as part of a South American gravity circuit, with a base at Madison, Wisconsin. The Bouguer values reveal a 45 mgal positive anomaly zone to the north of Caracas, and an east-west trending 40 mgal negative zone in the central part of the area. Inaccuracies in the values obtained for some of the southernmost stations resulted from lack of true elevation figures and inadequate topographic control. The anomalies are discussed on the basis of the presently known geology and with reference to the strong negative belt paralleling the West Indian island arc.

Floyd M. Soule (U. S. Coast Guard Oceanographic Unit, Woods Hole, Mass.) Recent Oceanographic Work of the United States Coast Guard in the Western North Atlantic--In the ice-berg seasons of 1954 and 1955 (February-July) the United States Coast Guard assigned the CGC Evergreen as oceanographic vessel for supplying dynamic topographic and isothermal charts of the vicinity of the Grand Banks in connection with the International Ice Patrol, using its own records and those from passing steamers. In 1954, this work ended in early July, and in late August and early September, the Evergreen occupied 79 additional oceanographic stations in the Labrador Sea and the western North Atlantic. The observations used in preparing the charts have also been used in analyses of T-S relationships and in further work on the relationships of the cold wall in the Grand Banks region, the strength of the Labrador Current, the sea level at Bermuda and Charleston, heat transport, and the circulation in the area. The data for 1954 will be published in U. S. Coast Guard Bulletin 40, with a discussion of the related problems studied. The work of 1955 is now well along.

C. R. Sparger (Department of Oceanography, Texas A and M College, College Station, Texas) A Relationship between Wind and Heat Change Observed in a Vertical Column of the Sea--A comparison has been made of certain local heat changes as given by differences between two five-day-average thermal profiles and wind stresses computed from observed velocities. Data were gathered at a single station in the North Atlantic Ocean during the autumn months of 1947 and 1948. Significant findings were as follows. The wind stress was apparently unrelated either to the heat change occurring within the mixed layer or, separately, to that occurring below. But there seemed to be a connection between the cumulative effect of wind stress acting during one week and the total heat-change to 200 meters the following week. For both years studied it was possible to find a direction such that components of the wind in that direction vary in sign as the heat-change. The directions were different for the two years. A significant correlation was found to exist between the magnitude of the appropriate component of stress and the heat-change, having taken the lag into account. Conclusions are that advection was important in explaining the heat changes described, and that horizontal gradients of heat-content, averaged for several days, had a relatively stable orientation in the region investigated. Though a lag of some sort between wind action and the response of the water as reflected in heat-change is intuitive and is borne out here, a satisfactory theoretical explanation has yet to be presented.

Robert W. Stallman (Ground Water Branch, U. S. Geological Survey, Washington 25, D. C.) Numberical Analysis of Regional Water Levels to Define Aquifer Hydrology--The hydrology of an aquifer must be known in some detail if its development as a source of water supply is to be carried out efficiently. Quantitative field studies are now made to estimate the rate of recharge and the hydraulic constants. These constants, which indicate the ability of the aquifer to transmit and store water, are obtained by means of special field tests, such as pumping tests. A combination of information on them and data on the geology can be used to estimate the rate at which water can be withdrawn from any point in the aquifer and also to calculate the effect of that withdrawal on the entire flow system. In order to define a nonhomogeneous aquifer hydraulically by the techniques now used, a large number of expensive field tests would have to be made. Inability to make them may preclude detailed planning of ground-water development, even though the need for such planning becomes more urgent as the overall cost of ground-water development increases. A method of calculating the rates of change of the hydrologic parameters in space for a nonhomogeneous aquifer in two-dimensional flow is given. The method is based on application of numerical analysis to water-level data. Combination of this method with a limited number of pumping tests permits the quantitative definition of the aquifer hydrology. Even though the aquifer size or extent is unknown, the analysis may be applied as a prospecting tool for locating areas of high transmissibility within a specified region. The potential value of such a method of analysis emphasizes the need for collecting detailed and accurate water-level data in all quantitative ground-water investigations.

J. F. Steukert (Bureau of Aeronautics, Project AROWA, Naval Air Station, Norfolk, Va.) An Observational Program to Meet Certain Research Requirements on Tasks in Progress at Project AROWA--The present observational program is not adequate to meet certain research requirements. Modifications or additions to the present program are suggested in the following research problems: (1) to explain certain phases of cyclogenesis; (2) to improve tropical storm forecasting; (3) to improve forecasting over ocean areas by changes and additions in the ocean-ship program to fit dimensions of weather systems for which forecasts are required; (4) an approach to forecasting at and above the 100 millibar level; (5) wind forecasting, particularly in connection with the jet stream.

E. Dixon Stroup and Thomas S. Austin (U. S. Fish and Wildlife Service, Honolulu, Hawaii) Review of the Oceanographic Programs of the Pacific Oceanic Fishery Investigations--The Pacific Oceanic Fishery Investigations (POFI), U. S. Fish and Wildlife Service, has, since early 1950, been engaged in oceanographic surveys of the tropical and subtropical central Pacific, and since last year the northern temperate central Pacific. These studies support POFI's exploratory fishing program, stressing the location of areas of enrichment and increased productivity in the upper layers. The tabulated data from the cruises, together with vertical sections of the measured fields and brief descriptive texts, are published as Special Scientific Reports of the U. S. Fish and Wildlife Service. In the tropical central Pacific, standard oceanographic work is nearing completion, with reports published on seven cruises crossing and defining the equatorial current system (lat. 15°N-10°S, long. 140°W-180°). Similar reports on seven cruises in Hawaiian Islands offshore waters and three cruises to temperate waters north of Hawaii (Lat. 25°N-40°N, long. 140°W-170°E) are in preparation. Plans for 1955 include a reconnaissance oceanographic cruise to the equatorial eastern Pacific in cooperation with Scripps Institution of Oceanography and the Peruvian Hydrographic Office, and participation in NORPAC, a joint survey of the entire Pacific north of 20°N latitude during July, August, and September by POFI, SIO, the State of California, University of Washington, Pacific Oceanic Group of Canada, and Japanese agencies.

Hall Taylor (Department of Geology, Columbia University, New York 27, N. Y.) Rock Deformation by Gravitational Sliding--Recent work by Merla, Migliorini, Maxwell, Baldry, and others indicates that gravitational sliding over some parts of the Earth's crust has caused sheet-like blocks, many cubic kilometers in volume, to move almost horizontally across the Earth's surface for distances measured in tens of kilometers. Oceanographic research by Ewing, Heezen, Kuenen, Shepard, and others has shown that masses of sediment may, by means of slumping or turbidity currents or both, move long distances along ocean bottoms which have only very slight slopes. Movement occurs most extensively in shaly layers, although other lithologies are also represented. A synthesis of these findings suggests that (1) folded strata lying over less folded layers may reflect large scale gravity sliding and need not be associated with a compressive force applied from some distant source; and (2) low angle overthrust faults may in part result directly from gravity sliding, and only indirectly from distant and deep seated tectonic forces within the Earth.

C. W. Thornthwaite and J. R. Mather (Laboratory of Climatology, Elmer, N. J.) Evaporation Investigations at the Laboratory of Climatology--The methods of measuring potential evapotranspiration and of computing it from readily available climatic data have undergone a thorough re-investigation during the course of an intensive program to develop a world-wide network of evapotranspiration measuring stations. As a result of recent improvements in instrumentation and observations it appears feasible to employ the energy balance method, long used in computing evaporation, in making estimates of the maximum possible water loss from different vegetative-covered areas. Certain modifications of the present evapotranspiration bookkeeping procedure are made which permit the determination of the fluctuations in soil moisture from saturation to the wilting point and which take into account the different moisture holding capacities of different soils. The method is also employed in computing the movement of moisture through different levels in a soil profile.

G. R. Tilton and L. T. Aldrich (Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.) The Reliability of Zircons as Age Indicators--Age measurements have been made on six zircon samples which include isotopic analyses of the lead. The results are as follows:

Locality	Source	Age in millions of years			
		U238/Pb206	U235/Pb207	Pb207/Pb206	Th232/Pb208
Tory Hill, Ontario	granite	1020	1050	1060	390
Tory Hill, Ontario	syenite	940	987	1015	. . .
Capetown, S. Africa	granite	330	354	525	237
Bagdad, Arizona	granite	630	770	1210	270
Gunnison, Colorado	granite	930	1130	1500	515
Ceylon	pegmatite	540	544	555	538

The Ceylon material was a single gem-grade crystal, the Tory Hill granite zircon crystals were two to three millimeters in length while all the remaining zircon samples were crystals which passed a 200-mesh sieve. There is indication of an effect which is related to grain size. Where discrepancies occur among the various ages for a single sample, the Pb/Pb age is believed to be the more nearly correct, since it gives the best correlation with K/A and Rb/Sr ages on the same rock. If this is true, the ages measured by the alpha activity-total lead method which closely resemble the U238/Pb206 ages given above are incorrect for four of the samples listed.

David K. Todd and Leung-ku Lau (Division of Civil Engineering, University of California, Berkeley, Calif.) On Estimating Streamflow into a Tidal Estuary--Because standard stream-gaging procedures using stage-discharge relations cannot be applied to measure streamflow in a tidal estuary where currents reverse direction with each tidal cycle, other methods are required. Continuous velocity traverses across a section are satisfactory, but this method is laborious and costly. A method for estimating streamflow is described based upon continuous salinity recorder data, tide-gage data, and current tables. These data, combined with particular correction factors to make the information applicable to the entire cross-section, permit streamflow estimates to be prepared rapidly. To illustrate the procedure, streamflows from the Sacramento-San Joaquin Valley, California, entering San Francisco Bay at Carquinez Strait are computed. Results are compared with measured flows obtained by the California Water Project Authority. The sources of error, applications, and limitations of the method are outlined.

Willis L. Tressler and Bernard K. Swanson (U. S. Navy Hydrographic Office, Washington, D. C.) Polar Oceanography--During January, February, and March, 1954 the icebreakers U.S.S. *Atka* (AGB-2) and U.S.S. *Edisto* (ABG-3) occupied 93 oceanographic stations during an investigation of the physical oceanography and ice conditions in the waters to the southwest and east of Greenland. Ten bottom samples were obtained across the Greenland-Iceland ridge. This area was further investigated by the *Edisto* during February-March, 1955. Antarctic oceanography was conducted as a part of the Hydrographic Office's program carried out aboard the U.S.S. *Atka* (AGB-2) during the United States Antarctic Expedition, 1954-1955.

K. K. Turekian (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) The Abundance of Strontium in Granitic and Basaltic Rocks--A general method of quantitative analysis applicable to all silicate rocks has been developed for strontium. The method yields precision of ± 5 pct and good accuracy when compared with available samples determined by the isotope dilution technique. After the calcium content of the rock is determined spectrographically the rock is mixed with an equal portion by weight of $CaCO_3$ which has been highly purified of Sr by ion exchange separation. The high Ca content tends to minimize the differential interference effects of granitic and basaltic compositions on the Sr4607 resonance line used in the analysis. No internal standard *per se* is used but the Ca4579 line is used as a 'monitoring' line since the behavior in the DC arc of these two lines has been shown to be almost identical despite their different energy levels. The DC arc is run at 16 amps to prevent excitation of the Sr4607 line during the burning of the alkali portion. The Sr4607/Ca4579 ratio is then used for analysis compared to a standard curve. The values for the standard granite G-1 and the standard diabase W-1 are 265 ppm Sr and 110 ppm Sr respectively. The significance of the analysis of approximately 100 samples of basaltic and granitic rocks will be discussed with relation to such problems as lognormal distribution and regional variation. The average value for basaltic rocks is reported as 500 ppm and 200 ppm for granitic rocks.

M. A. Tuve and H. E. Tatel (Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.) Seismic Crustal Exploration, Colorado Plateau, and Wasatch-Uinta Mountains--We have extended our continental seismic survey of crustal structure to the southern part of the Colorado Plateau and the eastern rim of the Great Salt Lake Basin. The average elevations were 4500-7000 ft and 6500 ft, respectively. Shots in Santa Rita, New Mexico, and Morenci, Arizona, were observed along several radiants. Critical reflections were observed at 108 km and total reflections beyond; the P_n were traced out to 300 km with a cross over at 145 km to the south and 175 km to the north. The depth of the lower crustal (Mohorovicic) discontinuity is thus at 28 km to the south and 34 km to the north (10 - 15 pct greater if corrected for increase of velocity with depth). In Utah we recorded shots from Bingham Canyon but no reflections were observed. The shots were weak. The cross over is at about 135 km and the discontinuity depth is about 29 km. Similar measurements in the east have shown the crustal depth to be at greater depth (40 km) with lesser surface height (2000 ft). We conclude that the Pratt and Airy hypotheses, while they may have limited regional applicability, are not in their present form descriptive of whole continental structures.

G. J. Wasserburg (Institute for Nuclear Studies, University of Chicago, Chicago, Ill.) and R. J. Hayden (Argonne National Laboratory, Lemont, Ill.) A^{40} - K^{40} Dating--A comparison between the A^{40} - K^{40} age and the Pb-U age of a co-existing feldspar and a uraninite from Branchville, Conn., were determined using the method described previously. The A^{40}/K^{40} ratios obtained for two aliquots of a microcline from this locality were 0.0166 and 0.0170. The ages calculated using a branching ratio of 0.85 and a decay constant $\lambda = 0.55 \times 10^{-9}$ years^{-1} were 350 and 356 million years, respectively. The Pb^{206}/U^{238}, Pb^{207}/U^{235}, and Pb^{208}/Th^{232} ages obtained for the uraninite were 367, 365, and 318 m y, respectively. A feldspar from Kinkel Quarry, Bedford, N. Y., gave an A^{40}/K^{40} ratio of 0.0177 and an age 370 m y. This value is in good agreement with the

Pb-U ages determined on a cyrtolite from this locality by Nier. The A^{40} - K^{40} age of a glauconite from the Franconian formation (Cambrian) was determined. An A^{40}/K^{40} ratio of 0.0290 and an age of 573 m y was obtained. This value is 30 pct greater than the age for the Cambrian used by earlier workers. A search was made for radiogenic Xe^{129} in the Beardsley chondritic meteorite. It was not present to more than 1.3×10^{-11} stp cc/gm. Using a value of 1 ppm by weight iodine in the meteorite and assuming that I^{129} was originally formed in the same abundance as I^{127}, this indicates that the time interval between the formation of the elements and the last crystallization of the meteorite was greater than 4.1×10^8 years.

G. W. Wetherill, G. R. Tilton, G. L. Davis, and L. T. Aldrich (Department of Terrestrial Magnetism and Geophysical Laboratory, Carnegie Institution of Washington, Washington, D. C.) Comparison of Radioactive Age Measurements on Pegmatites--Some measurements which we have reported recently indicate that Rb^{87}/Sr^{87} ages are consistently higher than K^{40}/A^{40}ages on the same mineral specimen. Because of uncertainties in the decay constants of K^{40} and the ability of the mineral to retain argon, it is difficult to interpret the meaning of these results. In order to obtain further information on the reliability of age determinations using the Rb^{87} disintegration, ages of micas and feldspars are being compared with reliable ages of uraninites collected from the same pegmatite. The Rb^{87}/Sr^{87} age of the lepidolite from Bob Ingersoll Pit No. 1, Black Hills, South Dakota, was found to be 2050 ± 150 m y as compared to 1600 ± 50 m y for the uraninite. The U^{238}/Pb^{206} agreed with the U^{235}/Pb^{207} age within two per cent. The Rb^{87}/Sr^{87} age of biotite from the Fission mine, Wilberforce, Ontario, was found to be 1180 ± 90 m y. This can be compared with Nier's values of 1077 m y for the U^{238}/Pb^{206} age and 1035 m y for the Pb^{207}/Pb^{206} age. As in the K^{40}/A^{40} comparisons, the Rb^{87}/Sr^{87} ages seem high by from 10 to 30 pct. Possible explanations of this difference will be discussed.

John H. Wiggins, Jr. (U. S. Air Force and Institute of Technology, St. Louis University, St. Louis, Mo.) Variations in Time Delay between Detonations as a Factor in Quarry Blast Vibrations--Certain seismic phases, produced by different millisecond delay quarry blasts, were identified and compared by Fourier analysis and other, more conventional methods. The only variable between the test shots was time delay. The results of the investigation showed that compressional energy is increased, shear energy is possibly reduced, and surface waves are decreased in amplitude as the time delay is changed from 0.015 to 0.030 sec. Some possible conclusions affecting the results are discussed.

Ronald E. Wilcox (Columbia University, New York 27, N. Y.) Petrochemistry of Amphibolites of the Bakersville-Roan Mountain Area, North Carolina--In this area, metadiabases and ortho-amphibolites are associated with para-amphibolites. The former are metamorphosed basaltic dikes which cut quartzofeldspathic Cranberry gneiss. The para-amphibolites belong to the Roan formation and were found by Brobst (1953) to be of sedimentary origin. The Roan overlies the Cranberry formation conformably. The Roan-Cranberry boundary consists of interlayered amphibolite and gneiss in a zone one to three miles wide. The basaltic dikes strike obliquely across the Roan-Cranberry boundary. Few dikes can be recognized in Roan amphibolite, but over 200 dikes form a well-defined dikeswarm in the Cranberry gneiss. Amphibolites of uncertain origin are found in the boundary zone along the strike of the dikeswarm. Lapadu-Hargues (1953) suggests that ortho-amphibolites and para-amphibolites can be distinguished by their bulk chemical composition. The Engels (1951) indicate that the two types of amphibolites might be distinguished by their content of certain trace elements. Twenty amphibolites and metadiabases have been analyzed chemically; two hundred and fifty samples have been analyzed spectrographically for Ga, Ba, Ni, Co, and Cr. The results show that the metadiabases and ortho-amphibolites cannot be distinguished chemically from Roan para-amphibolites.

Allan F. Wilson (University of Western Australia, Nedlands, Western Australia, and Visiting Professor, Indiana University, Bloomington, Indiana) The Significance of Some Minor Structures in Australian Charnockitic Rocks--A major cause of confused nomenclature for charnockitic rocks is that petrographic studies have been supported by inadequate field observations. In areas of poor outcrop, failure to recognize the nature and significance of boudins of basic granulite has lead too often to 'continuous' dykes and sills of 'igneous' basic charnockite being shown on maps. Many of the occasional narrow salic streaks seen in some large areas of apparently massive (and hence supposedly 'igneous') basic charnockite are found on structural analysis to be tightly folded lenses. Interpretation of the microfolds is consistent with the fold pattern revealed by mapping contacts of associated metamorphic rocks. Moreover, there is usually sufficient orientation of hyperthene and other minerals to demonstrate that the bulk of these rocks are metamorphic and have not crystallized under 'hydrostatic pressures.' The lineation is sensibly parallel to major original fold axes. In some acid hyperthene granulites current-bedding has been recognized. Such rocks contain a complex zircon suite typical of meta-sediments and may be interbedded with khondalites and kinzigites. Although most Australian charnockitic rocks appear to be meta-igneous and meta-sedimentary rocks, field mapping shows that there are many square miles of magmatically emplaced acid charnockites in Central Australia.

George P. Woollard (University of Wisconsin, Madison, Wis.) Areas of Current Tectonic Activity in the United States--A compilation of earthquakes in the United States based upon all published catalogues and the extensive unpublished material collected by the late Harry Fielding Reid show that there are definite lineaments of tectonic activity as indicated by recurring earthquakes. Some of these lineaments, as that associated with the San Andreas Fault system, are well known, but there are others associated with fault systems not generally recognized as being active as the line of late Paleozoic overthrust faults on the western border of the Appalachian Mountains. Other lineaments of activity are not connected with any known fault systems. This activity is independent of the regional tilting of the continent as revealed by level line measurements in the Great Lakes Region and tide gage readings along the coasts.

E. J. Workman and W. Drost-Hansen (New Mexico Institute of Mining and Technology, Socorro, N. Mex.) On the Micro-Structure and Formation of Ice from Liquid Water--Pure ice samples formed from liquid water are invariably found to consist of bundles of parallel prisms of hexagonal symmetry. (The dimensions of the units are approximately three microns in width and five microns in length.) The formation of this micro-structure is independent of the rate of freezing, and is believed to be by a dislocation mechanism; during growth vacancies condense into disk-shaped voids which, upon collapse, create dislocation rings. This mode of formation is affected by the presence of small amounts of alkali-halide in the water. As an example, for increasing concentration of CsF, the micro-structure becomes less pronounced and it is completely absent for a 10^{-3} M solution. This phenomenon is associated with the selective incorporation of halide ions into the ice from the solution. As a result of this selective incorporation of negative ions, a potential difference develops between advancing ice surface and the solution. When incorporated, the halide ions, besides influencing the micro-structure, greatly affect the electrical conductivity of ice as well as the mechanical properties.

Claude E. ZoBell (Scripps Institution of Oceanography, University of California, La Jolla, Calif.) The Danish Galathea 'Round-the-World Deep Sea Expedition--During the period from October 15, 1950, when the Galathea left Copenhagen, until its return on May 31, 1952, the Expedition obtained about 40,000 nautical miles of echograms, several thousand miles at depths exceeding 4000 meters. Detailed topographical surveys were made of the Philippine Trench, Java Trough, Weber Deep in the Banda Sea, Solomons Deep, Kermadec-Tonga Trench, and the Porto Rican Deep. Although the main objective of the Expedition was investigating animal life at great depths, it made hundreds of hydrographic stations, determinations of primary productivity by the C-14 technique, collections of deep-sea sediments and plankton hauls along the course. Representatives of 25 animal orders were found for the first time at depths exceeding 6000 meters, including numerous species of fish taken at depths down to 7300 meters. Actinia, Amphipoda, Holothurioidea, Lamellibranchiata, Sipunculoidea, and Tanaidacea were taken from depths exceeding 10,000 meters. Bacterial populations ranging from thousands to millions per gram were demonstrated in moist mud from the bottom of the aforementioned deeps. Most of these bacteria proved to be barophiles which grow only at hydrostatic pressures virtually isobaric with the environment from which taken, namely, 700 to 1000 atmospheres.

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NOTES AND PERSONALIA

NOTES

World Symposium on Applied Solar Energy--As already announced [Trans. v. 35, p. 863], a Symposium on Applied Solar Energy will be held in Phoenix, Arizona, November 1-5, 1955, under the sponsorship of the Association for Applied Solar Energy, the Stanford Research Institute, and the University of Arizona. The program includes outstanding scientists working in this field from all parts of the country and from Australia, Israel, England, South Africa, France, Japan, and perhaps other countries. Those interested should write to Dan MacLachlan, Stanford Research Institute, Stanford, California.

Guenter Loeser Memorial Lecture--The Geophysics Research Directorate of the Air Force Cambridge Research Center has established a series of Guenter Loeser Memorial Lectures to commemorate Guenter Loeser, a scientist of the Directorate who gave his life in research work in 1953. The first Guenter Loeser Memorial Lecturer was Jean I. F. King, whose address was given in Boston on June 2, 1955, on 'The vertical temperature distribution on the Earth, Venus, and Mars.' The Lecturer is to be a staff member of the Geophysics Research Directorate who, in the judgment of a special committee, has made an outstanding contribution to geophysics.

Progress on the CERN project--The Convention for the Establishment of a European Organization for Nuclear Research (CERN) [Trans. v. 35, p. 1007] has now been ratified by all of the 12 eligible European nations, who have notified UNESCO of their decision to participate in the research activities on the peaceful uses of atomic energy to be conducted at Geneva. Those participating are Belgium, Denmark, France, German Federal Republic, Greece, Italy, Jugoslavia, The Netherlands, Norway, Sweden, Switzerland, and the United Kingdom.

Magnolia Petroleum Company scholarships--Two new scholarships valued at $750 each have been established in the fields of geology and petroleum engineering at the University of Texas for the school year 1955-56 by this company. These are in addition to several others granted by the Company to assist outstanding students in geophysics and other fields closely related to geophysics and the petroleum industry. The scholarships in geophysics are offered at the Colorado School of Mines, Georgia Institute of Technology, Kansas State College, Missouri School of Mines, Texas Technological College, and Texas A and M College.

Reoccupation of Ice Island T-3--Ice Island T-3, which was discovered and occupied for several months by American scientists, has been reoccupied for the summer months of 1955. The Island was abandoned in May, 1954, when it floated to a point near the northern tip of Ellesmere Island close to one of the fixed weather stations. While it has not moved far in the intervening period, a new project of investigation has been set up to obtain not only surface weather and solar radiation data but to study marine biology of the Arctic Ocean and obtain gravitational, magnetic, and oceanographic data, and to make related studies with respect to the Island.

International Arid Lands meeting--The International Arid Lands meeting was held at Albuquerque, New Mexico, April 26-28, and, following an inspection tour, was resumed at Socorro, New Mexico, for the period May 2-4, 1955. Scientists from 12 countries discussed the problems of the arid areas of the Earth, noting that one-third of the total land area of the world is either arid or semiarid. The meeting was sponsored by the Southwestern and Rocky Mountain Division of the American Association for the Advancement of Science and by the Advisory Committee on Arid Zone Research of UNESCO. It was supported by UNESCO funds and grants from the Rockefeller Foundation and the National Science Foundation.

PERSONALIA

Carl I. Aslakson, Captain, U. S. Coast and Geodetic Survey, retired on May 1, 1955, after an outstanding career of more than 30 years. His recent work has had largely to do with the use of shoran in geodesy, and in this connection the readers of the Transactions are acquainted with his recent paper on determination of a new value for the speed of light.

Donald M. Baker, Consulting Engineer of the Los Angeles firm of Ruscardon Engineers, has received a Certificate of Merit from the Urban Land Institute as a result of a national competition.

Dirk Brouwer, Professor of Natural Philosophy at Yale University and Director of the Yale Observatory, has been given the Gold Medal of the Royal Astronomical Society and delivered the George Darwin lecture on The Motions of the Outer Planets.

Harrison S. Brown, Professor of Geochemistry at the California Institute of Technology, has been elected to membership in the National Academy of Sciences.

Ven Te Chow, Professor of Civil Engineering of the University of Illinois and Chairman of our Section of Hydrology's Committee on Runoff, has been named the recipient of the Epstein Award which is made available to a member of the faculty of the Civil Engineering Department of the

University for professional development. Under this award he will visit several important hydraulic laboratories in this country to obtain ideas and information that will contribute to the further development of the program in teaching and research at the University of Illinois.

Richard O. Eaton, Chief Technical Adviser of the Beach Erosion Board, has been named a member of a board of three on a technical mission to Africa including Monrovia, Liberia, and Gambia. This is one of the activities of the Foreign Operations Administration.

Maurice Ewing, Director of the Lamont Geological Observatory of Columbia University and Vice President of the American Geophysical Union, was recently given the Alexander Agassiz Medal of the National Academy of Sciences for his work in marine geophysics.

Jack B. Graham has resigned his position with the Water Resources Division of the U. S. Geological Survey and has accepted partnership in a company of consulting ground-water geologists which has been renamed Leggette, Brashears, and Graham with headquarters in New York. His work with the company began last year. Only recently has he been taken into partnership.

Beno Gutenberg, Professor of Geophysics and Director of the Seismological Laboratory of the California Institute of Technology, has recently received the degree of Doctor of Philosophy, honoris causa, from Uppsala University in Sweden.

M. King Hubbert, Research Geologist of the Shell Oil Co., Houston, Texas, has been elected to membership in the National Academy of Sciences.

O. W. Israelsen, formerly Professor of Irrigation at Utah State College and now Consultant with the Agricultural Development and Engineering Services at Logan, Utah, is devoting a year to work at the Roorkee University in India setting up a postgraduate course in irrigation.

J. Wallace Joyce has resigned his position in the Department of Defense on the staff of the Assistant Secretary of Defense for Applications Engineering to accept the position as head of the Office for the International Geophysical Year of the National Science Foundation.

Phillip Z. Kirpich has left his work as Resident Manager for Knappen-Tippetts-Abbett-McCarthy Engineers in Athens and has accepted the position as Chief Engineer of Corporación Autonoma Regional del Cauca at Cali, Colombia. This corporation is under contract with his former firm and two others in connection with the multiple-purpose development of Colombia's water resources much along the lines of the Tennessee Valley Authority.

August W. Raspet, Professor of Mechanical Engineering and Head of the Department of Aerophysics at Mississippi State College, delivered a lecture on 'The sailplane in boundary layer research' before the Royal Institute of Technology in Stockholm, Sweden, on April 5. En route, he attended a Conference on Aviation Research at the National Physical Laboratory, Teddington, England, and on his return he visited Germany and France for conferences with leaders on aerodynamics research.

R. Dana Russell has resigned his position as Geophysicist and Chairman of the Scientific Planning Board of the U. S. Navy Electronics Laboratory in San Diego, California, to accept a position as Head of Geological Research with the Ohio Oil Company with headquarters in Denver. Before his departure from California, a commendation for meritorious service to the Navy was presented to him.

George E. P. Smith, Professor of Agricultural Engineering at the University of Arizona, retired in January, 1955, following more than 50 years of service with the University. Since 1944 he has been engaged in research at the Agricultural Experiment Station.

Thomas F. Thompson, formerly Division Geologist with the South Pacific Division of the Corps of Engineers, has recently resigned and accepted a position as Resident Engineer with the Ralph M. Parsons Co. in New Delhi, India, where his work will be concerned with explorations for the development of ground water.

Harold C. Urey, Professor of Chemistry at the Institute of Nuclear Studies of the University of Chicago and 1934 Nobel prize winner in chemistry, has been given the Dickinson College Priestley Memorial Award for 1955.

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THIRTY-SIXTH ANNUAL MEETING (1955)

MINUTES, GENERAL ASSEMBLY AND SECTION MEETINGS

SMOKER

A Smoker was held in the Ball Room of the National Press Club, National Press Building, Fourteenth and F Streets, N. W., Washington, D. C., on Monday, May 2, 1955, starting at 20h 30m. About 350 were in attendance. No program was presented, and the gathering was entirely informal and served to provide opportunity for those in attendance to form ever-changing small discussion groups.

EVENING SESSION

The Evening Session of the Thirty-Sixth Annual Meeting was called to order by President James B. Macelwane at 20h 00m, Tuesday, May 3, 1955, in the Lecture Room of the National Academy of Sciences, 2101 Constitution Avenue, N. W., Washington, D. C. About 175 were in attendance. After appropriate welcoming remarks, President Macelwane presented Geoffrey A. Kellaway, Principal Geologist of the British Geological Survey and Museum, who presented the first paper on the Symposium on Ice, this comprising the first session of that Symposium. The interesting and informative address by Dr. Kellaway was on the subject of Structural and Geomorphological Effects Produced by the Action of Frost and Ice (see abstract in the Reviews, Abstracts, and Bibliography of this issue). Following this, President Macelwane called on Maurice Ewing to present the citation of Walter Hermann Bucher as the Seventeenth Recipient of the William Bowie Medal. President Macelwane then made the presentation, and in the absence of the recipient in Europe, General Secretary John Putnam Marble was designated as his proxy. He responded with appropriate comments, reading the telegram received from the recipient. The proceedings are set forth in the opening pages 383-384, of this issue.

The session then adjourned and was followed by an informal social hour with refreshments in the Auditorium of the National Academy of Sciences.

SESSION OF MOVING PICTURES OF GEOPHYSICAL INTEREST

In 1954, the Section of Oceanography arranged a session on recent films of geophysical interest which was well received. As a result, the arranger of last year's program, Charles C. Bates, was asked to arrange another session this year, broadening the scope appropriately. The following films were presented:

United States Air Force: Military Climatology (black and white; 22 minutes)
United States Weather Bureau: Tornado Warnings (black and white; 11 minutes)
Gerrit Damms: History of Weather Movements, 1899-1939 (black and white; 5 minutes)
Stanford Research Institute: The City that Disappears (color; 28 minutes)
United States Corps of Engineers: Speaking of Models (color; 14 minutes)
University of California: Sea Water Intrusion (color; 25 minutes)
University of California: Surf Safety: Riptides (black and white; 12 minutes)
United States Navy: Naval Photography in Science (color; 25 minutes)
Undersea Research Group: Aqualung Diving off Marseilles, France (color; 25 minutes)

The session was attended by about 250.

GENERAL ASSEMBLY: SECOND SESSION OF SYMPOSIUM ON ICE AND BUSINESS MEETING

The General Assembly was called to order by President Macelwane at 14h 00m, Wednesday, May 4, 1955, in the Auditorium of the National Academy of Sciences. About 200 were in attendance.

The President turned over the chair to Gordon G. Lill, Secretary of our Committee on Meetings, who was active in the arranging of the Symposium on Ice. The Symposium proceeded as follows, recognizing Geoffrey A. Kellaway's paper of the previous evening as (1) of the series.

(2) E. J. Workman and W. Drost-Hansen: On the Micro-Structure and Formation of Ice from Liquid Water (presented by Walter Drost-Hansen)
(3) Robert P. Sharp: The Behavior of Ice in Glaciers
(4) Max C. Brewer: Geothermal Investigations of Permafrost in Northern Alaska
(5) Henry Bader: Research on the Physical Properties of Ice

Following the presentation of each paper, opportunity was given for discussion which was rather lively at times. (The abstracts of the papers are found in the Reviews, Abstracts, and Bibliography of this issue of the Transactions.)

Following the Symposium, President Macelwane resumed the chair and called the Business Meeting to order. The minutes of the Thirty-Fifth Annual Meeting [see Trans. v. 35, pp. 534-536] were approved.

Report of the General Secretary--General Secretary Marble briefly summarized activities since the Thirty-Fifth Annual Meeting, pointing out that these are reported in connection with the minutes of the meetings of the Executive Committee of December 4, 1954 [see Trans., v. 36, pp. 156-168, 1955] and May 1 and 4, 1955 (to be published in the August, 1955 issue of the Transactions) He announced the total formal registration at the Thirty-Sixth Annual Meeting as 1087, with perhaps 1300 in attendance. A recapitulation of changes in membership since May 1, 1954, was as follows:

Memberships, May 1, 1954	5040	
New members, May 1, 1954 to April 27, 1955 (including applications in process)	352	
Reactivated	7	5399
Resigned	174	
Dropped	125	
Inactive	5	
Deceased	25	329
Membership as of April 27, 1955		5070

The names of those deceased are listed in the reports of meetings of the Executive Committee, and brief obituaries are carried as news items in the Transactions.

Reports of Standing Committees

Meetings--Chairman John N. Adkins could not be in attendance, but coming meetings were reported as follows:

North Central Regional Meeting, to be held at Iowa City, Iowa, June 16-17, 1955.

Mid-Pacific Regional Meeting (Geophysical Society of Hawaii), its first general meeting, to be held in Honolulu, Hawaii, November 15-17, 1955.

Pacific Northwest Regional Meeting, to be held in Portland, Oregon, November 18, 1955.

Southeastern Regional Meeting, to be held in Atlanta, Georgia, in connection with the meeting of the AAAS, December 27-29, 1955.

Pacific Southwest Regional Meeting, to be held probably at the University of California in Los Angeles in late January or early February, 1956.

It was announced that the Thirty-Seventh Annual Meeting will be held in Washington, D. C., April 30-May 2, 1956.

Reports of other Standing Committees were not presented; they will be published in the Transactions as received.

Reports of Special Committees

Resolutions--Chairman E. H. Vestine presented five resolutions, all of which were unanimously adopted as follows:

(1) RESOLUTION OF THANKS FOR THE USE OF FACILITIES

WHEREAS, The District of Columbia Chapter of the American Red Cross has provided the use of its Auditorium for the Thirty-Sixth Annual Meeting of the American Geophysical Union, therefore be it

RESOLVED, That the American Geophysical Union express its great appreciation of this cooperation and instructs the General Secretary to express the thanks of the Union to the appropriate official.

(2) RESOLUTION OF THANKS FOR THE USE OF FACILITIES

WHEREAS, The National Academy of Sciences and the United States Public Buildings Administration have provided the use of meeting rooms and other services for the Thirty-Sixth Annual Meeting of the American Geophysical Union, therefore be it

RESOLVED, That the American Geophysical Union express its great appreciation of this cooperation, extended over many years, and instructs the General Secretary to express the thanks of the Union to the appropriate officials.

(3) RESOLUTION OF THANKS TO THE UNIVERSITY OF CALIFORNIA

WHEREAS, The success of the Pacific Southwest Regional Meeting at Berkeley, California, on February 4 and 5, 1955, was due in large part to the space and facilities generously provided by the University of California, therefore be it

RESOLVED, That the thanks of the American Geophysical Union be extended to the University of California for the use of their meeting rooms and other facilities, and that the General Secretary be instructed to forward a copy of this resolution to Dr. Robert Gordon Sproul, President.

(4) RESOLUTION OF THANKS TO THE CARNEGIE INSTITUTION OF WASHINGTON

WHEREAS, The Carnegie Institution of Washington has for many years provided office space for the American Geophysical Union, without which the Union could not adequately function, therefore be it

RESOLVED, That the American Geophysical Union express its deep appreciation of this continued assistance and instructs the General Secretary to express its thanks to the appropriate officers of the Carnegie Institution of Washington.

(5) RESOLUTION ON TIME-SIGNAL SERVICE

WHEREAS, There is a vital need in all seismological and geodetic work for accurate time service, and

WHEREAS, The time service maintained by the U. S. Naval Observatory, the Naval Communications Service, and the National Bureau of Standards has been of great use in this work, therefore be it

RESOLVED, That the American Geophysical Union express its appreciation of the valuable scientific cooperation and reiterate its desire for the continuance of this time-signal service, and be it further

RESOLVED, That copies of this resolution be sent to the Secretary of the Navy, the Director of Naval Communications, the Superintendent of the Naval Observatory, the Secretary of Commerce, and the Director of the National Bureau of Standards.

No reports of other Committees, Sections, or other groups were presented; information relating to these as reported to the Executive Committee is found in the Executive Committee minutes.

Adjournment--The meeting was adjourned at 16h 00m.

JOHN PUTNAM MARBLE, General Secretary
WALDO E. SMITH, Executive Secretary

APPENDIX A-- MINUTES OF THE ANNUAL MEETING OF 1955; SECTION OF GEODESY, AMERICAN GEOPHYSICAL UNION

President Hoskinson called the meeting to order in the Auditorium of the National Academy of Sciences at 09h 04m on May 4, 1955. There being no objection from the floor, and no corrections received, the President declared the minutes of the 1954 meeting approved as published in the Transactions [v. 35, p. 537, 1954].

The President announced the appointment of the Committee on Nominations [H. W. Hemple, Chairman; Floyd W. Hough; Harry H. Hess] which will meet later in the year to select nominees for offices of the Section for the next triennium.

The scientific session proceeded with the reading of the following papers:

(1) R. A. Hirvonen: On the Precision of the Gravimetric Determination of the Geoid
(2) Samuel D. Owen: Net design for Hiran Surveys, read by Ernest J. Parkin
(3) William E. Bonini[a] and George P. Woollard: A comparison of Two High-Range Geodetic Type Gravimeters
(4) John C. Rose[a] and George P. Woollard: Results with the Gulf Pendulums Over the North American Gravity Standardization Range
(5) William Markowitz: Analysis of the Variable Rotation of the Earth for 1951 to 1954
(6) R. J. Smith: Gravity Cross-Section of the Venezuelan Coast Ranges, read by Harry H. Hess
(7) Philip C. Doran: Recent Developments in Geodesy

[a] Denotes speaker.

After the close of the scientific session James A. Peoples, Jr. introduced a resolution on time-signal service for action by the Section. This was the same resolution approved by the Section of Seismology. This was approved and forwarded to the Union [see Resolution (5) above].

The meeting adjourned at 11h 25m.

FRANK L. CULLEY, Secretary

APPENDIX B--MINUTES OF THE ANNUAL MEETING OF 1955, SECTION OF SEISMOLOGY, AMERICAN GEOPHYSICAL UNION

The Thirty-Sixth Annual Meeting of the Section of Seismology was held on May 2, 1955 at 09h 00m in the Auditorium, District of Columbia Chapter, American Red Cross. President Heinrich called the meeting to order and the following business was transacted:

The minutes of the 1954 meeting were approved as published in the Transactions [v. 35, p. 537, 1954].

President reported briefly on the Rome meeting of IUGG and stated that he had sent a written report to the office of the Union.

L. M. Murphy, Chairman of the Resolutions Committee, presented a resolution for consideration by the Section. It was approved and forwarded to the Union [see Resolution 5, above]. (As 1956 is election year, President Heinrich has appointed the following Committee on Nominations: Frank Neumann, Chairman; H. F. Birkenhauer; Frank Press.)

This concluded the business session which was immediately followed by the presentation of the following scientific papers:

(1) M. A. Tuve and H. E. Tatel: Seismic Crustal Exploration, Colorado Plateau, and Wasatch-Uinta Mountains.
(2) John H. Wiggins, Jr.: Variations in Time Delay between Detonations as a Factor in Quarry Blast Vibrations
(3) Frank Press and Maurice Ewing: Maximum Group Velocity of Rayleigh Waves between 60 and 80 Seconds.
(4) Palmer W. Carlin: A Computer for Microseismic Azimuths
(5) William Mansfield Adams: The Reeff Horizontal Seismograph and Its Calibration
(6) Dean S. Carder: Earthquake Recording in a Deep Mine
(7) Thomas J. Hickley, Richard R. Ross and John J. McCue: A Telemeter for Seismic Recording
(8) Frank Neumann: Sensitivity Controls on Sprengnether Seismographs (read by L. M. Murphy)
(9) Paul Leiber and Arthur Farmer: On Wave Propagation in Granular Media

JAMES A. PEOPLES, JR., Secretary

APPENDIX C--MINUTES OF THE ANNUAL MEETING OF 1955 SECTION OF METEOROLOGY, AMERICAN GEOPHYSICAL UNION

The Thirty-Sixth Annual Meeting of the Section of Meteorology was held on May 2-4, 1955, in the Auditoria of the National Academy of Sciences, General Services Building, and the American Red Cross Building.

The business session was called to order at 14h 00m, May 2, 1955, by President Phil E. Church.

Since no corrections were received, the Chairman declared the minutes of the Thirty-Fifth Annual Meeting of the Section of Meteorology approved as published in the Transactions [v. 35, p. 537, 1954]. The Chairman then appointed a Committee on Resolutions (J. R. Gerhardt, Chairman; Vincent Oliver; R. H. Simpson). (As the next elections will be held in February, 1956, President Church has appointed the following Committee on Nominations: Robert D. Fletcher, Chairman; Philip F. Clapp; Robert G. Fleagle.)

Brief reports of special committees were given as follows:

Atmospheric Diffusion--Plans are in the making for a survey of literature in the fields of eddy motions and diffusion.

Cloud Physics--This Committee has been instrumental in setting up a conference on 'Physics of Cloud and Precipitation Particles' to be held in September, 1955, at Woods Hole, Mass.

Upper Atmosphere--A report has been submitted on the scope of the upper atmosphere (and related) observational program for the IGY.

Joint American Geophysical Union - American Meteorological Society Committee on the Interaction of the Sea and Atmosphere--This Committee arranged for the two symposia on 'Normal and Tangential Strasses Near the Air-Sea Interface' and 'Meteorologically Induced Changes in Water Level' held during the spring meetings (see minutes, Section of Oceanography); is actively considering the problem of instrumentation of the 'Texas Towers'.

The business meeting was then adjourned and was followed by the scientific sessions as follows:

Scientific Sessions

Severe Storms (Chairman, A. K. Showalter)

(1) Conrad P. Mook: A Synoptic Study of the Surface Gusts Associated with the Passage of a Hurricane Overland (20 minutes)
(2) Lester F. Hubert: 'Frictional' Filling of Hurricanes (20 minutes)
(3) Walter Hitschfield and J. S. Marshall: A Possible Role of Hail in the Development of Tornadoes (20 minutes)
(4) Nicholas E. Manos: Tornadoes Spread Disease (25 minutes)
(5) Frank B. Dinwiddie: Some Aspects of Waterspout Behavior at Nags Head, N. C. (20 minutes)
(6) J. B. Holleyman, J. M. Hand, and A. Caporaso: The 1954 Micro-Network of Washington, D. C. for the Study of Pressure Jump Lines on a Small Scale (20 minutes)
(7) Norman Hagen: Notes on the Record Losses from 1954 Hurricanes (5 minutes)

Symposium on Observational Requirements in Meteorology (Chairman, Robert Fletcher)

(8) Bruce Gilchrist: Observational and Transmission Requirements for Numerical Weather Prediction (25 minutes)
(9) Joseph Kaplan and G. F. Schilling: Motions in the High Atmosphere (25 minutes)
(10) Robert C. Bundgaard: The Required Accuracy of Weather Observations in Jet Aircraft Operations (25 minutes)
(11) Robert C. Bundgaard and Keith Veigas: Synoptic Observations around 40,000 Feet (10 minutes)
(12) John C. Bellamy: Meteorological Observational Requirements for Flight Planning (25 minutes)

Symposium on Observational Requirements in Meteorology (Chairman, Gordon C. Cartwright)

(13) John R. Gerhardt and K. H. Jehn: On the Problem of Determining the Spatial Distribution of Small Scale Atmospheric Phenomena from Point Measurements with Application to Field Radio Meteorology (20 minutes)
(14) Harold B. Harshbarger: Climatological Requirements for Meteorological Observations (25 minutes)
(15) J. F. Steukert: An Observational Program to Meet Certain Research Requirements on Tasks in Progress at Project AROWA (20 minutes)
(16) Leon Sherman and Noel E. LaSeur: Observational Requirements of Tropical Meteorology (20 minutes)
(17) W. Boynton Beckwith: Hail Observations in the Denver Area (20 minutes)

WOODROW C. JACOBS, Secretary

APPENDIX D--MINUTES OF THE ANNUAL MEETING OF 1955, SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY, AMERICAN GEOPHYSICAL UNION

The Thirty-Sixth Annual Meeting of the Section of Terrestrial Magnetism and Electricity of the American Geophysical Union was held on May 2, 1955. The first session was called to order at 09h 10m in the Lecture Room of the National Academy of Sciences by Vice President H. R. Joesting. There were approximately 80 members and guests in attendance. The minutes of the previous meeting were approved as published in the Transactions [v. 35, p. 538, 1954].

Vice President Joesting opened the business meeting by stating that the next election will be held in February, 1956 and that a Committee on Nominations had been appointed consisting of J. W. Joyce, Chairman; N. C. Gerson; A. G. McNish; E. B. Roberts; and E. H. Vestine. He then called for a discussion regarding a possible change in the name of the Section. It was pointed out that the name of the former International Association of Terrestrial Magnetism and Electricity has been changed to the International Association of Geomagnetism and Aeronomy. A lively discussion followed culminating in a motion offered by L. R. Alldredge to recommend to the Executive Committee of the AGU that the name of Section D be changed to Section of Geomagnetism and Aeronomy. This motion was seconded and during the ensuing discussion an amendment to this motion was offered by David Knapp to the effect that the name should include the term Geoelectricity and hence the name should be Section of Geomagnetism, Geoelectricity, and Aeronomy. In the voting which followed, the amendment carried but the motion failed. Finally the chairman agreed to appoint a committee to study the problem of a name for the section and to submit recommendations at the next annual meeting.

After routine announcements the scientific program listed below was presented.

(1) B. B. Phillips, P. A. Allee, J. C. Pales, and R. H. Woessner: An Experimental Analysis of the Effect of Air Pollution on the Conductivity and Ion Balance of the Atmosphere
(2) Gerald R. MacCarthy: Natural Earth Potential Anomalies near Point Barrow, Alaska
(3) Irwin Roman: The Apparent Resistivity of a Single Uniform Overburden
(4) Lewis M. Branscomb and Stephen J. Smith: Atomic Oxygen Negative Ion Affinity and Photodetachment Cross Section
(5) Helen B. Pettit and Edward Manring: Intensity Variations of (OI) 5577 and Sodium D in the Nightglow
(6) N. C. Gerson: Radio Observations of the Aurora
(7) Willard H. Bennett: The Störmertron (this paper was concluded with a working demonstration)

The session adjourned at 12h 00m with many lingering on to view in a personal way the exhibit presented as part of Paper (7).

The second session was called to order at 14h 05m in the Lecture Room of the Natural Academy of Sciences by L. R. Alldredge. It was announced that a committee consisting of E. O. Hurlburt, Chairman; Ross Gunn; David Knapp; and N. C. Gerson had been appointed to consider a possible name change for the Section. The technical program listed below was then presented.

(8) Victor Hess, Vincent J. Kisselbach, and Henry A. Miranda, Jr.: Beta Rays from the Atmosphere
(9) Howard M. Caulk: An Electron Beam Magnetometer
(10) Marcus H. Norwood and Edwin J. Chernosky: A Numerical Geomagnetic Flux and Activity Recording System
(11) Edwin J. Chernosky: The Day-to-Day Variability of Magnetic Activity
(12) David Knapp and James H. Nelson: A notable Transient Perturbation on the Magnetograms of January 17, 1955
(13) Walter M. Elsasser and H. Takeuchi: Non-uniform Rotation of the Earth and Geomagnetic Drift
(14) Scott E. Forbush and E. H. Vestine: Daytime Enchancement of Size of Sudden Commencements and of Initial Phase of Magnetic Storms at Huancayo
(15) R. E. Holzer and O. E. Deal: Low Audio-Frequency Electromagnetic Radiation of Natural Origin

Each paper was presented by the first named author except for Paper (8) which was presented by Henry A. Miranda, Jr. The meeting was adjourned at 17h 00m.

L. R. ALLDREDGE, Secretary

APPENDIX E--MINUTES OF THE ANNUAL MEETING OF 1955 SECTION OF OCEANOGRAPHY, AMERICAN GEOPHYSICAL UNION

The Thirty-Sixth Annual Meeting of the Section of Oceanography was called to order by Vice-President Walter Munk at 14h 00m on May 2, in the Auditorium of the General Services Building. President Richard Fleming was unable to attend this Annual Meeting. Since no corrections had been received the minutes of the 1954 meeting were declared approved as published in the Transactions [v. 35, p. 538-539, 1954].

John Lyman stated that several other countries had presented excellent reports of their national oceanographic effort at the Rome meetings of the I.U.G.G. and moved that a committee be appointed to prepare a National Report on Oceanography for presentation at the coming Buenos Aires meetings of I.U.G.G. This motion was passed.

He also discussed certain problems which arose at the Rome meetings because of lack of clear rules regarding delegation of voting powers for the Section at the International meetings. Richard Fleming, who as our President carried the voting power for the United States, also has an office in the International Association, and could not always represent the Section because of his other duties. A motion was made and passed to have a committee investigate the necessary change in rules in regard to the delegation of the vote for the Section in International meetings.

Chairman Munk stated that a discussion of plans for the International Geophysical Year in the field of Oceanography, which was on the agenda, would be deferred since Gordon Lill was to present a paper on this subject during the scientific sessions.

Secretary Pritchard reported on actions of the Executive Committee, American Geophysical Union.

Chairman Munk stated that the Nominating Committee for the election of officers next February had been appointed and was functioning. (The committee consists of D. E. Carritt, Chairman; W. V. Burt; A. C. Redfield; R. O. Reid.)

Chairman Munk expressed the view, held by a number of members, that in the future, meetings should be planed so that no two scientific sessions of the Section are held simultaneously.

The Business Meeting was then adjourned and was immediately followed by the Scientific Session, which included three sessions of a Symposium on Recent Oceanographic Cruises, and three sessions of a Symposium held jointly with the Section of Meteorology and planned by the Joint Committee on Air-Sea Boundary Problems. The scientific program as presented follows:

SECTION OF OCEANOGRAPHY

Symposium on Recent Oceanographic Expeditions (First Session, May 2, 1955, 14h 00m, Auditorium, General Services Building)

(1) Fred B. Phleger: Results of the Swedish Deep-Sea Expedition
(2) Claude E. Zobell: The Danish Galathea Round the World Deep Sea Expedition
(3) Harold E. Edgerton: Calypso Oceanographic Expeditions
(4) G. E. R. Deacon: The Discovery Investigations on the Southern Ocean
(5) W. H. Littlewood and Frede Hermann: The Danish Oceanographic and Fisheries Research Vessel Dana, and Its Postwar Program
(6) Luis R. A. Capurro: Recent Oceanographic Expeditions in Argentina
(7) Hugh J. McLellan: Major Offshore Projects of the Atlantic Oceanographic Group

Symposium on Recent Oceanographic Expeditions (Second Session, May 3, 1955, 09h 00m, Auditorium, National Academy of Sciences)

(8) A. P. Crary and Irene Browne: Arctic Ice Island Oceanographic Observations
(9) Floyd M. Soule: Recent Oceanographic Work of the United States Coast Guard in the Western North Atlantic
(10) Charles B. Officer: Cruise of the Research Vessels Atlantis and Caryn to the Caribbean, January-March 1955
(11) Maurice Ewing and Bruce C. Heezen: Deep Sea Expeditions of the Vema
(12) William W. Anderson and Robert B. Abel: Expeditions of the M/V Theodore N. Gill off the South Atlantic Coast of the U. S., 1952-1954
(13) Murray H. Schefer: Work of the Oceanographic Survey Unit
(14) Willis L. Tressler and Bernard K. Swanson: Polar Oceanography
(15) F. G. Walton Smith and Ilmo Hela: Oceanographic Work of the Marine Laboratory, Miami
(16) George B. Austin: Recent Oceanographic Cruises in the Gulf of Mexico

Symposium on Recent Oceanographic Expeditions (Third Session, May 3, 1955, 14h 00m, Auditorium, National Academy of Sciences)

(17) Ira T. Sanders: Recent Oceanographic Activities of the U. S. Coast and Geodetic Survey
(18) Roger Revelle, and Others: Scripps Deep Sea Expeditions 1950-54
(19) E. C. La Fond and H. W. Menard: Recent Oceanographic Expeditions Conducted by U. S. Navy Electronics Laboratory
(20) C. A. Barnes: Oceanographic Expeditions of the Brown Bear in the Northeast Pacific
(21) G. L. Pickard: British Columbia Inlets
(22) W. M. Cameron: Joint Canadian-United States Beaufort Sea Expeditions
(23) E. D. Stroup and T. S. Austin: Review of the Oceanographic Programs of the Pacific Oceanic Fishery Investigations
(24) Townsend Cromwell, and Others: Plans for Joint Operations in the Pacific during 1955
(25) Gordon G. Lill: A Tentative Program in Oceanography for the International Geophysical Year, 1957-1958

General Session (May 4, 1955, 09h 00m, Reading Room, National Academy of Sciences)

(26) Max C. Brewer: Preliminary Interpretations of Ice, Water, and Bottom Temperature Data in the Arctic Ocean near Barrow, Alaska
(27) Robert A. Gilcrest: An Approach to the Problem of Prediction of Net Weekly Ocean Temperature Change
(28) Gerhard Neumann: On Wind Generated Wave Motion at Subsurface Levels
(29) D. W. Pritchard: Contribution of Longitudinal Variations in Strength of Tidal Current to the Maintenance of a Mean Surface Slope in an Embayment
(30) Frank Chew: On the Offshore Circulation and a Convergence Mechanism in the Red Tide Region off the West Coast of Florida
(31) C. R. Sparger: A Relationship Between Wind and Heat Change Observed in a Vertical Column of the Sea
(32) Yasukazu Saito: The Theory of the Transient State Concerning Upwelling and Coastal Current

SECTIONS OF OCEANOGRAPHY AND METEOROLOGY

Symposium on Normal and Tangential Stresses Near the Air-Sea Interface (Chairman, B. Haurwitz; May 3, 1955, 09h 00m, Reading Room, National Academy of Sciences)

(1) Gerhard Neumann: Review of the Present Position and Problems of the Momentum Transfer across the Air-Sea Interface
(2) Ira A. Hunt: Transfer of Energy by Wind to a Water Surface
(3) Allen Schooley: Facet Separation Distributions of Wind-Created Water Waves
(4) Wilbur Marks and Joseph Chase: Observation of the Growth and Decay of a Wave Spectrum
(5) Walter H. Munk: Wind Stress on Water: An Hypothesis
(6) D. Lee Harris: The Effect of a Moving Pressure Disturbance on the Water Level in a Lake

Symposium on Meteorologically Induced Changes in Water Level (First Session) (Chairman, Walter H. Munk, May 3, 1955, 14h 00m, Reading Room, National Academy of Sciences)

(7) Arthur R. Miller: The Effect of Steady Winds on Sea Level at Atlantic City
(8) William E. Maloney and Raymond J. McGough: Meteorologically Induced Deviations from Predicted Tide Levels of Chesapeake Bay
(9) H. Arakawa: Japanese Forecasting of Changes in Sea Level Induced by Typhoons
(10) Robert O. Reid: Hurricanes: Their Storm Tide Potential, Wave Energy Index, and Probability
(11) Gordon W. Groves: Oscillations in Sea Level with a Period of a Day or More
(12) Walter H. Munk: Resume of the Stress Problem and Related Changes in Water Level

Symposium on Meteorologically Induced Changes in Water Level (Second Session) (Chairman, Charles C. Bates; May 4, 1955, 09h 00m, Auditorium, District of Columbia Chapter, American Red Cross)

(13) William von Arx and A. C. Redfield: Moving Picture: Flooding of Woods Hole, Massachusetts, during Hurricane Carol, 1954
(14) Maurice Ewing, Frank Press, and W. L. Donn: Air-Coupled Surface Waves
(15) A. C. Redfield and A. R. Miller: Water Levels Accompanying East Coast Hurricanes
(16) L. A. Farrer: Effect of Hurricane Winds on Water Levels in Lake Okechobee
(17) Theodore Francis Green: A Legislator Views the Storm Tide Problem
(18) Robert H. Simpson: U. S. Weather Bureau Plans for Research for the Hurricane Inundation Problem

DONALD W. PRITCHARD, Secretary

APPENDIX F--MINUTES OF THE ANNUAL MEETING OF 1955, SECTION OF VOLCANOLOGY, GEOCHEMISTRY, AND PETROLOGY, AMERICAN GEOPHYSICAL UNION

President Foshag called the meeting to order at 09h 04m, May 2, 1955, and announced that the recent mail ballot had shown an overwhelming majority in favor of the proposed change in the name of the Section. (The actual tally was 1880 in favor, 41 opposed [see Trans., v. 36, p. 374, April, 1955].) The Section of Volcanology thus officially becomes the Section of Volcanology, Geochemistry, and Petrology.

The president also announced appointment of a Nominating Committee consisting of H. W. Fairbairn, Chairman; P. H. Abelson; R. M. Garrels; G. C. Kennedy; and W. C. Krumbein, and urged members to submit the names of suggested nominees for section offices to Professor Fairbairn as soon as possible. Elections will take place in February, 1956.

The Secretary reported that the minutes of the Annual Meeting of 1954 had been published [Trans., v. 35, p. 539] and, as no corrections had been received, they were approved.

There being no further business, the business meeting was adjourned and the first technical session got under way at 09h 15m.

The program of technical papers was presented in four sessions as follows:

(1) R. M. Garrels, W. C. Krumbein, and H. A. Slack[a]: Transfer of Energy and Materials through Rocks
(2) Gilbert Corwin[a], L. D. Bonham, M. J. Terman, and G. W. Viele, Jr.: Geology of Pagan, Mariana Islands
(3) S. S. Goldich[a] and A. P. Ruotsala: Igneous Rock Series of Minnesota
(4) Allan F. Wilson: The significance of Some Minor Structures in Australian Charnockitic Rocks
(5) Ronald E. Wilcox: Petrochemistry of amphibolites of the Bakersville-Roan Mountain Area, North Carolina
(6) Eugene Callaghan and Ming-Shan Sun: Correlation of Igneous Rocks of New Mexico by Fusion Method
(7) Arie Poldervaart: Zircons in the Granite Series
(8) Fred M. Bullard: Volcanic Activity in Costa Rica and Nicaragua in 1954
(9) J. A. Jacobs[a] and D. W. Allan: Report on Thermal Investigations Being Carried out at the University of Toronto

Tuesday, May 3, 1955, 09h 00m

(10) K. K. Turekian: The Abundance of Strontium in Granitic and Basaltic Rocks
(11) Heinrich D. Holland[a] and Robert D. Hardin: On the Log-Normality of the Distribution of the Elements
(12) George W. DeVore: Surface Chemistry and Mineral Association
(13) D. T. Griggs[a], G. C. Kennedy, and W. S. Fyfe: A Simple Apparatus for High Pressure and Temperature; discussion of geological implications by W. S. Fyfe
(14) George W. Morey: The Action of Hot Water on Some Feldspars
(15) George C. Kennedy: Some Liquidus Temperatures in the System SiO_2-- FeO--H_2O
(16) J. R. Smith[a] and H. S. Yoder, Jr.: Variations in X-ray Powder Diffraction Patterns of Plagioclases
(17) R. I. Harker[a] and O. F. Tuttle: Some Experimental Data Applicable to the Metamorphism of Siliceous Limestone and Dolomite
(18) G. Kullerud: The FeS--ZnS System: A Geological Thermometer
(19) Arthur H. Lachenbruch: Dissipation of the Temperature Effect of Drilling a Well in Arctic Alaska

Tuesday, May 3, 1955, 14h 00m

(20) P. K. Kuroda: On the Activity Ratio of the Actinium Series to the Uranium Series Radioactive Elements
(21) Patrick M. Hurley: Scintillation Spectrometer II: Simultaneous Measurement of Uranium, Thorium, and Potassium in Common Rocks
(22) Bernard F. Armbrust[a], Jr., and P. K. Kuroda: On the Isotopic Constitution of Radium (Ra-224/Ra-226 and Ra-228/Ra-226) in Petroleum Brines
(23) Elizabeth Rona[a], L. O. Gilpatrick, and Lela M. Jeffrey: Uranium Analysis of Sea Water by Isotopic Dilution

(24) W. Compston and P. M. Jeffery[a]: The Carbon Reservoir and Isotope Abundance Fluctuations
(25) Clarence S. Ross, I. Friedman[a], and Robert L. Smith: The Origins of Water in Glassy Rocks as Determined from the Isotopic Composition
(26) Harmon Craig[a] and Donald E. White: The use of Calcite as an Isotopic Geothermometer
(27) Robert Clayton: Oxygen Isotope Abundances in Quartz and Calcite
(28) R. D. Russell[a] and G. L. Cumming: Lead Isotope Abundances

Wednesday, May 4, 1955, 09h 00m

(29) G. J. Wasserburg[a] and R. J. Hayden: A^{40} - K^{40} dating
(30) Leonard F. Herzog[a] and William H. Pinson, Jr.: The Rb and Sr Content and Geologic Age of Certain Biotites, and a Correction to the 'Cosmic' and 'Crustal' Abundances of Rb
(31) William H. Pinson[a], Jr., Milo M. Backus, and Leonard F. Herzog: The Rb and Sr Content and Geologic Age of Certain Lepidolites, and Their Radiogenic Ca^{40} Content
(32) G. L. Davis[a], G. W. Wetherill, and L. T. Aldrich: Age Measurements on Minerals from Granite
(33) G. R. Tilton[a] and L. T. Aldrich: The Reliability of Zircons as Age Indicators
(34) L. T. Aldrich[a], G. L. Davis, G. R. Tilton, and G. W. Wetherill: Comparative Radioactive Age Measurements of Igneous Rocks near Gunnison, Colorado
(35) G. W. Wetherill[a], G. R. Tilton, G. L. Davis, and L. T. Aldrich: Comparison of Radioactive Age Measurements of Pegmatites
(36) George L. Bate[a] and J. Laurence Kulp: Variations in the Isotopic Composition of Common Lead and the History of the Earth's Crust
(37) J. Laurence Kulp[a] and Walter R. Eckelmann: The Uranium-Lead Age Studies in the Lake Athabaska Region
(38) Wallace S. Broecker[a] and J. L. Kulp: Lamont Radiocarbon Investigations

[a] Denotes speaker.

Attendance at all of the sessions was excellent, and there was lively discussion of many of the papers.

FELIX CHAYES, Secretary

APPENDIX G--MINUTES OF THE ANNUAL MEETING OF 1955, SECTION OF HYDROLOGY, AMERICAN GEOPHYSICAL UNION

President Harold G. Wilm called the meeting to order at 09h 00m, May 2, 1955, in the Auditorium of the National Academy of Sciences. The minutes of the Annual Meeting of 1954 were published [see Trans. v. 36, pp. 540-541, 1954], and as there were no corrections, they were approved. The President called attention to fact that the terms of the present officers expire July 1, 1956; that a nominating committee consisting of Arthur Johnson, Chairman; Maurice L. Albertson; C. C. McDonald; Howard W. Lull; and Louis C. Gottschalk had been appointed; and that they would report to the Executive Committee by September 1, 1955.

Secretary Harry F. Blaney gave a brief report on the Tenth General Assembly, International Union of Geodesy and Geophysics at Rome, Italy, in September, 1954 and of the Pacific Southwest Regional Meeting, University of California, Berkeley, February, 1955. Walter B. Langbein reported on the program problems of the IUGG Rome meeting.

Walter Langbein as a member of the AGU Editorial Committee, gave a brief report of the work of that committee. Since there was no further business the program of the four technical sessions proceeded. The first session, under the chairmanship of H. G. Wilm got under way at 09h 50m, and adjourned at 11h 50m with about forty in attendance.

(1) Masao Shiotani[a] and Hideo Arai: Snowdrift Control by Shelterbelts
(R1) Leonard Schiff: Report of Research Committee on Infiltration
(2) F. A. Huff: Comparison between Standard and Small Orifice Gages; discussion by Walter B. Langbein and Harold G. Wilm
(3) Sam Shulits[a], C. D. Sims, Jr., and D. J. Stull: The Dilemma of Bed-Load Formulas
(4) F. A. Huff and J. C. Neill[a]: Areal Representatives of Storm Point Rainfall

The second session, under the chairmanship of William C. Ackermann, began at 14h 00m on May 2, 1955, in the Auditorium, District of Columbia Chapter of American Red Cross.

Symposium on Evaporation

(5) H. L. Penman: Estimating Evaporation (presented by T. van Hylckame); H. F. Blaney, Discussant
(6) C. W. Thornthwaite and J. R. Mather[a]: Evaporation Investigations at the Laboratory of Climatology; C. H. M. Van Bavel, Discussant
(7) G. Earl Harbeck: The Lake Mead Evaporation Study (presented by W. B. Langbein): W. U. Garstka, Discussant
(8) M. A. Kohler[a], T. J. Nordenson, and W. E. Fox: Evaporation from Pans and Lakes: F. F. Snyder, Discussant
(9) M. L. Albertson: Evaporation from a Free Water Surface (presented by G. H. Hickox); G. H. Hickox, Discussant

The session adjourned 16h 50m; about 80 were in attendance.

The third session, under the chairmanship of Frank C. Foley, began May 3, 1955, at 9h 00m, in the Auditorium, District of Columbia Chapter of American Red Cross.

Symposium on Ground-Water Fluctuation

(10) V. C. Fishel: Long-term Trends of the Ground-Water Levels in the United States
(11) M. I. Rorabaugh: Prediction of Ground-Water Levels on Basis of Rainfall and Temperature Correlations
(12) W. E. Clark: Forecasting the Dry-weather Flow of Pond Creek: a Progress Report
(13) R. W. Stallman: Numerical Analysis of Regional Water Levels to Define Aquifer Hydrology
(14) R. M. Richardson: Tidal Fluctuations of Water Level Observed in Wells in East Tennessee
(15) C. F. Merriam: Potential Value of Ground Water Data

The session adjourned 11h 45m; about 60 were in attendance.

The fourth session, under the chairmanship of Harry F. Blaney, began May 3, 1955, at 14h 00m, in the Auditorium, District of Columbia Chapter of American Red Cross.

(16) Leonard Schiff: The Status of Water Spreading for Ground Water Replenishment
(17) D. E. Outlaw[a] and E. C. Rhodehamel: Pine Barrens Research Project, New Jersey
(18) M. S. Hantush: Analysis of Data from Pumping Tests in Leaky Aquifers
(R2) Arthur Johnson: Report of Research Committee on Glaciers
(19) D. K. Todd[a] and Leung-Ku-Lau: On Estimating Streamflow into a Tidal Estuary
(20) H. E. Schwarz: Flood Volume Frequency Estimates
(21) J. C. Maxwell: The Bifurcation Ratio in Horton's Law of Stream Numbers

[a] Denotes speaker

The session adjourned at 16h 45m with closing remarks by President Wilm; about 70 were in attendance.

HARRY F. BLANEY, Secretary

APPENDIX H--MINUTES OF THE ANNUAL MEETING OF 1955, SECTION OF TECTONOPHYSICS, AMERICAN GEOPHYSICAL UNION

The business session was called to order at 14h 00m, May 2, 1955, in the Reading Room, National Academy of Sciences Building, by President Birch. The minutes of the 1954 meeting were approved as published [Trans. v. 35, p. 541, 1954]. (As the next elections will be held in February, 1956, President Birch has appointed the following Committee on Nominations: C. R. Longwell, Chairman; Ernst Cloos; M. K. Hubbert; L. L. Nettleton.)

There being no further business, the scientific session followed immediately. The following papers were presented:

(1) Hall Taylor: Rock Deformation by Gravitational Sliding
(2) G. D. Garland and L. G. D. Thompson: Geological Implications of Gravity Anomalies over the Grenville and Northern Appalachian Regions of Quebec
(3) Iris Y. Borg and John C. Maxwell: Interpretation of Fabrics of Experimentally Deformed Sands
(4) Jack F. Evernden: Finite Strain Theory and the Earth's Interior

(5) B. F. Howell, Jr.: Origin of the Continents
(6) Hans Ramberg: A Study of Boudinage Structures
(7) George P. Woollard: Areas of Current Tectonic Activity in the United States
(8) E. N. Silverman and T. F. Bates: X-ray Diffraction Study of Orientation in the Chattanooga Shale

JAMES T. WILSON, Secretary

CHANGES AND CORRECTIONS RELATING TO COMMITTEES OF THE UNION AND THE SECTIONS

In Part 2 of the Transactions of December, 1954, Committees of the Union and the Sections are noted on pages 125-128. Changes and corrections are recorded as follows:

EXECUTIVE COMMITTEE OF THE UNION

Add Helmut E. Landsberg; remove Robert Balk (deceased).

STANDING AND SPECIAL COMMITTEES OF THE UNION

Nominations: Helmut E. Landsberg, Chairman, replacing Walter H. Bucher, who remains as a member of the Committee.
Award of the William Bowie Medal: Jno. A. Fleming was inadvertently omitted.

REGIONAL COMMITTEES

Pacific Southwest Regional Committee: C. F. Woffinden has resigned because of removal from the Region; the Committee has voted not to replace him.
Pacific Northwest Regional Committee: Frank Neumann has resigned and has not been replaced.
Mid-Pacific Region (Geophysical Society of Hawaii): John F. Mink (President), Dan A. Davis (Vice President), Lawrence E. Eber (Secretary-Treasurer), W. R. Crawford, Howard S. Leak, and David S. Johnson

COMMITTEES OF THE SECTIONS

Meteorology

Interactions of the Atmosphere with the Sea (joint committee with the Section of Oceanography and the American Meteorological Society): Add Willard J. Pierson, Jr., and Alfred H. Woodcock.
Cloud Physics: Add Charles E. Anderson.
Nominations: Robert D. Fletcher (Chairman), Philip F. Clapp, and Robert G. Fleagle

Terrestrial Magnetism and Electricity

Nominations: J. Wallace Joyce (Chairman), N. C. Gerson, A. G. McNish, Elliott B. Roberts, and E. H. Vestine

Oceanography

Nominations: D. E. Carritt (Chairman), W. V. Burt, A. C. Redfield, and R. O. Reid

Volcanology, Geochemistry, and Petrology

Nominations: H. W. Fairbairn (Chairman), P. H. Abelson, R. M. Garrels, G. C. Kennedy, and W. C. Krumbein

Hydrology

Nominations: Arthur Johnson (Chairman), Maurice L. Albertson, Louis C. Gottschalk, Howard W. Lull, and C. C. McDonald

Dynamics of Streams: Add Whitney M. Borland (1957), Norman H. Brooks (1957), and Arthur T. Ippen (1957)
Glaciers: Add W. C. Warren (1957).
Infiltration: Add James H. Brown (1957)

Tectonophysics

Nominations: Chester R. Longwell (Chairman), Ernst Cloos, M. King Hubbert, and L. L. Nettleton

PACIFIC SOUTHWEST REGIONAL MEETING, UNIVERSITY OF CALIFORNIA, BERKELEY, FEBRUARY 4-5, 1955

The Pacific Southwest Region held its Annual Meeting, February 4-5, 1955, with about 200 in attendance. Twenty papers bearing on meteorology, oceanography, and hydrology were presented in the program. Included were symposia on the Hydrology and Oceanography of San Francisco Bay, and on Snow and Watershed Management. The paper by J. F. Poland and G. H. Davis on Subsidence of Land Surface in the Delano and Mendota-Huron Areas, San Joaquin Valley, California, received wide attention in the California press. The abstracts of the papers presented were published in the April issue of the Transactions, pages 351-355.

Action was taken to hold the meeting in 1956 at the University of California at Los Angeles, and to approve the changes in the By-Laws of the Region for the establishment of the Mid-Pacific Regional Branch (see Continuation of the Report of the Committee on Statutes and By-Laws, in the April issue of the Transactions, pp.374-378).

SEMINAR IN HYDROLOGY AT PORTLAND STATE EXTENSION CENTER OF OREGON STATE COLLEGE ARRANGED BY PACIFIC NORTHWEST REGIONAL COMMITTEE

A seminar in Hydrology was planned and arranged by the Pacific Northwest Regional Committee in cooperation with the School of Engineering at Oregon State College. Eleven weekly evening meetings were held, beginning March 30, each about three hours in length conducted by specialists in the various aspects in hydrology. The various Federal agencies concerned with water resources participated in the presentation of the problems and techniques of the agencies, and the hydrologic principles involved. More than forty took the course. Arrangements were worked out by C. C. McDonald, Chairman, and his Regional Committee, in cooperation with Assistant Dean M. Popovich of Oregon State College.

ADDITIONS TO THE MEMBERSHIP, NOVEMBER 10, 1954 TO MAY 10, 1955

Adams, Mr. Thomas C., 1831 San Juan Ave., Berkeley 7, Calif. (ag)
Ajwani, Mr. Hashu J., Maithon-Dam, Bihar, India (g)
Aldrich, Dr. Lyman Thomas, 5241 Broad Branch Rd., N. W., Washington 15, D. C. (f)
Al-Hamdani, Mr. Ali, Knappen-Tippetts-Abbett-McCarthy Engineers, 62 W. 47th St., New York 36, N. Y. (ceg)
Allen, Mr. Harold A., 4304 Teton St., Boise, Ida. (befgh)
Amante, Mr. Anthony F., 5117 Belmont St., Houston 5, Tex. (bh)
Anderson, Dr. David V., 82 Indian Rd. Cresc., Toronto 9, Ont., Canada (beg)
Armbrust, Mr. Bernard F., Jr., 1640 N. Garland St., Fayetteville, Ark. (f)
Broscoe, Mr. Andy J., 1818 S. Raleigh St., Denver 19, Colo. (g)
Brown, Mr. James H., 7113 Halray Ave., Whittier, Calif. (g)
Carr, Mr. Robert B., c/o Arabian American Oil Co., Dhahran, Saudi Arabia (abd)
Chimiak, Lt. C. Dr. Walter, U. S. Navy Hydrographic Office, Washington 25, D. C. (e)
Chovitz, Mr. Bernard H., 10408 Brunswick Ave., Silver Spring, Md. (a)
Chow, Dr. Tsaihwa J., Dept. of Oceanography, University of Washington, Seattle 5, Wash. (eg)
Clark, Capt. Albert R., Hq. 9th Weather Group, Andrews AFB, Md. (ce)
Coroniti, Mr. Samuel C., 14 Canterbury Rd., Waltham, Mass. (cd)
Croom, Mr. Herman Lee, 3317 Old Dominion Blvd., Alexandria, Va. (c)
DesJardins, Mr. Robert B., Inst. of Atmospheric Physics, University of Arizona, Tucson 25, Ariz. (c)
Dickson, Mr. Frederic H., 65 Heights Ter., Fair Haven, N. J. (d)
Dowling, Mr. George B., 3204 W. 13th St., St. Andrew, Fla. (e)
Doyle, Prof. Frederick J., 1675 Roxbury Rd., Columbus 12, Ohio (a)
Dryden, Mr. Warren A., 442 43rd St., Brooklyn 32, N. Y. (ceg)
Edgerton, Mr. Roy Clarence, 1067 Edgewater St., Salem, Ore. (g)
Forgotson, Mr. James Morris, Jr., 208 Ricou-Brewster Bldg., Shreveport, La. (h)
Franks, Mr. Paul C., U. S. G. S., P. O. Box 360, Grand Junction, Colo. (fh)
Gain, Mr. Edward J. A., 6023 Enright Ave., St. Louis 12, Mo. (g)

Galloway, Mr. Sherman Elsworth, 4507 11th St., N. W., Albuquerque, N. Mex. (g)
Gaskill, Mr. Irving Elwell, 4836 Mac Arthur Blvd., N. W., Washington 16, D. C. (a)
Gimlett, Mr. James Irwin, 679 Vera Cruz Ave., Los Altos, Calif. (abdfh)
Goodman, Mr. Jerome, 105 E. 13th Ave., Columbus, Ohio (efgh)
Hack, Dr. John T., U. S. Geological Survey, Washington 25, D. C. (g)
Hansen, Sgt. Frank V., U. S. 56 208 988, 9577th TSU, Det., 1, Hq. Co., White Sands Proving Ground, N. Mex. (c)
Harris, Mr. Donald Gibson, 322 Williams Hall, N. C. State College, Raleigh, N. C. (c)
Harrison, Mr. Arthur E., Electrical Engineering Dept., University of Washington, Seattle 5, Wash. (g)
Harrison, Mr. Philip Wyman, 1112 E. 61 St., Chicago 37, Ill. (efgh)
Haushild, Mr. William L., 1205 Charles St., Worland, Wyo. (g)
Heidel, Mr. Sumner G., 3610 Otoe St., Lincoln, Nebr. (g)
Hembree, Mr. Charles Herbert, 6728 Y St., Lincoln, Nebr.(efg)
Hendricks, Mr. Gerald F., Medical Arts Bldg., Columbus, Ind. (g)
Henry, Prof. Harold R., Civil Engineering Dept., Michigan State College, East Lansing, Mich. (g)
Honig, Lt. Julius, 348 Stewart Gardens, Stewart AFB, Newburgh, N. Y. (c)
Hooper, Prof. Leslie James, 31 Highland Ave., Holden, Mass. (g)
Hore, Mr. F. Robert, P. O. Box 70, Ridgetown, Ont., Canada (g)
Hubbell, Mr. David Wellington, 1961 Calvert St., Lincoln, Nebr. (g)
Hucke, Sr. Ricardo, Direccion de Riego, Morande 71, Santiago, Chile (bdg)
Hulburt, Mr. Edward McPherson, Box 186, R. F. D. 2, Upper Marlboro, Md. (e)
Ingram, Dr. Roy L., Dept. of Geology, University of North Carolina, Chapel Hill, N. C. (eg)
Ireton, Mr. Hap W., 3822 Woodhead St., Houston 6, Tex. (cg)
Jenkins, Mr. David K., 2924 S. Buchanan St., Arlington, Va. (a)
Johnson, Mr. Curtis E., P. O. Box 513, Bakersfield, Calif. (g)
Jones, Prof. Don Barber, School of Civil Engineering, Georgia Institute of Technology, Atlanta, Ga. (g)
Kanz, Mr. Elmer, P.O. Box 1702, Balboa, Canal Zone, (abcg)
King, Mr. Erke C., 1201 W. Ada Pl., Denver, Colo. (g)
Kinsman, Mr. Blair, Riva, Md. (e)
Kodaira, Dr. Yoshio, Central Meteorological Observatory, Otemachi, Chiyoda-Ku, 1, Tokyo (cg)
Laurila, Dr. Simo Heikki, 1483 Coronet Dr., Columbus, Ohio (ac)
Lee, Mr. Shuh-Chai, National Taiwan University, Taipei, Taiwan, China (acg)
Lewellen, Mr. William H., 38 West Norwich Ave., Columbus, Ohio (g)
Lewicke, Mr. Victor, 4836 Mac Arthur Blvd., Washington 16, D. C., (acd)
Lilly, Mr. J. Edwin, Geodetic Survey, Dept. of Mines and Tech. Surveys, Ottawa, Canada (a)
Lundgren, Prof. H., Hydraulic Laboratories, Technical University of Denmark, 10 Oester Voldgade, Copenhagen K, Denmark (eg)
Magnuson, Mr. Harold R., 114 Surrey Lane, Westfield, N. J., (bfg)
Mahmud, Mr. Sarwar, Geological Survey of Pakistan, P. O. Box 15, Quetta, Pakistan (abcdg)
McBirney, Mr. Alexander Robert, 1036 Haight St., San Francisco, Calif. (f)
McLeod, Mr. J. D., Water Resources Div., Laurentian Bldg., 54 Albert St., Ottawa, Canada (cg)
Melton, Mr. Mark A., 1010 Chautauqua, Norman, Okla. (g)
Miesch, Mr. Alfred T., U. S. Geological Survey, P. O. Box 360, Grand Junction, Colo.(fh)
Mills, Mr. Zimri E., 823 N. Curtis Rd., Boise, Idaho (g)
Mostafa Elassiouty, Mr. Ibrahim M., Knappen-Tippetts-Abbett-McCarthy Engineers, 62 W. 47th St., New York 36, N. Y. (g)
Mozayeny, Mr. Mostafa, Bureau of Reclamation, Room 52 D, Building 53, Denver Federal Center, Denver, Colo. (g)
Murauchi, Mr. Sadanori, 48 Komagome-sendagi-cho, Bunkyo-ku, Tokyo, Japan (bf)
Myers, Mr. Lloyd E., Jr., Agricultural Experiment Sta., University Sta., Reno, Nev. (cg)
Nixon, Mr. Paul Robert, 203 Pammel Court, Ames, Iowa (cg)
Osborn, Mrs. B. B., Lamont Geological Observatory, Palisades, N. Y. (b)
Pettit, Dr. John T., P. O. Box 521, Encino, Calif. (ab)
Redding, Mr. Vernon Lewis, 5209 Huisache St., Bellaire, Tex. (bch)
Reigner, Mr. Irvin C., P. O. Box 1151, Kingston, Pa. (g)
Richgels, Mr. Henry John, Chevron Oil Co., P. O. Box 903, Laramie, Wyo. (abd)
Robles, Mr. Edward G., Jr., Lab. Branch, 7280th Maintenance Group, Box 53, c/o P. M., APO 30, New York, N. Y. (cdefg)
Roever, Mr. William L., 3737 Bellaire Blvd., Houston 25, Tex. (bd)
Rutstein, Mr. Milton Samuel, P. O. Box 24, Woods Hole, Mass. (e)
Schaeffer, Mr. Oliver A., Brookhaven National Lab., Upton, L. I., N. Y. (f)
Schleh, Mr. Heydorn James, 2522 W. Seybert St., Philadelphia, Pa. (ae)
Schneider, Mr. William J., 5729 Indianola Ave., Worthington, Ohio (g)

Sears, Mr. Harold A., 504 Waugh Dr., P. O. Box 13243, Houston, Tex. (b)
Seeger, LTJG Charles R., U. S. S. Samuel B. Roberts (DD823), FPO. New York, N. Y. (abcdefh)
Sen, Dr. Saurindranath, Department of Geology, 559 Schermerhorn Rd., Columbia University, New York 27, N. Y. (efh)
Shaw, Dr. Robert H., Agronomy Dept., Iowa State Coll., Ames, Iowa (cg)
Shearer, Miss Barbara J., Museum of Comparative Zoology, Harvard College, Oxford St., Cambridge, Mass. (ce)
Shykind, Mr. Edwin B., 5114 W. Greenleaf Ave., S. Skokie, Ill. (g)
Sodano, Mr. Emanuel M., 8105 Riverside Ave., Cabin John, Md. (a)
Southwick, Mr. Leonard R., Honolulu Magnetic Observatory, P. O. Box 117, Ewa, Oahu, Hawaii (abd)
Stauder, Rev. William Vincent, S. J., 221 N. Grand Blvd., St. Louis 3, Mo. (bcd)
Stewart, Mr. Samuel Woods, 124 Quackenbos St., N. W., Washington 11, D. C. (bd)
Sybers, Mr. William A., Tony, Wisc. (g)
Tatom, Capt. John F., Staff Aerologist CINCLANT Naval Base, Norfolk, Va. (ce)
Taylor, Mr. Samuel Guy, Jr., Geophysics Dept., Stanford University, Stanford, Calif. (b)
Townsend, Mr. William Howard, 302 Graceford Dr., Aberdeen, Md. (bc)
Trimble, Mr. George R., Jr., Northeastern Forest Exp. Sta., Laconia, N. H. (g)
Van Wynen, Dr. Jacobus C., Apartado 19, Maracaibo, Venezuela (bh)
Veronis, Dr. George, Institute of Advanced Study, Princeton, N. J. (ce)
Voth, Mr. Theodore H., 4315 E. 30th St., Tulsa 14, Okla. (g)
Warner, Dr. Lawrence A., Dept. of Geology, University of Colorado, Boulder, Colo, (fh)
Wennekens, Mr. M. Pat, Dept. of Oceanography, University of Washington, Seattle 5, Wash. (e)
Williams, Mr. Jerome, RFD 2, Cape St. Clair, Annapolis, Md. (e)
Willis, Dr. David G., 2518 Southgate St., Houston 25, Tex. (abdgh)
Yaeger, Mr. Oscar Blaine, 232 E. F St., North Little Rock, Ark. (g)
Zimmerman, Mr. Aaron L., 3416 N. E., 87th Pl., Portland 20, Ore. (cg)

Transferred to Active Status

Ference, Dr. Michael, Jr., Scientific Lab., Ford Motor Co., P. O. Box 2053, Dearborn, Mich. (cdh)
Garrison, Mr. Louis E., Narragansett Marine Lab., University of Rhode Island, Kingston, R. I. (e)

NATIONAL RESEARCH COUNCIL

AMERICAN GEOPHYSICAL UNION

STATUTES AND BY-LAWS

(Originally adopted at organization in 1919 and as amended to April 30, 1955)

PREAMBLE

The American Geophysical Union is hereby established by the National Research Council. It supersedes the "American Section of the proposed International Geophysical Union." The American Geophysical Union is the American National Committee of the International Union of Geodesy and Geophysics and the Executive Committee of the American Geophysical Union is the Committee on Geophysics of the National Research Council.

STATUTES

Article 1: Objects--(a) To assist in carrying out the objects of the International Union of Geodesy and Geophysics, which are: To promote the study of problems concerned with the figure and physics of the Earth; to initiate and coordinate researches which depend upon international cooperation, and to provide for their scientific discussion and publication; and to facilitate special researches.

(b) To promote, coordinate, and facilitate the study of the various branches and interrelationships of geodesy and geophysics in the United States of America, its outlying territories, and the ocean; to provide for scientific discussion, publication, and dissemination of information relative to these fields through the Transactions of the American Geophysical Union and other means.

Article 2: Bequests, Grants, Contributions, and Funds--The Union, upon approval of the National Research Council, may receive bequests, grants, contributions, and funds and may make disbursements therefrom, upon approval of the National Research Council.

Article 3: Membership--The membership of the American Geophysical Union shall be as follows:

(a) Members--(1) Those who composed the membership of the "American Section of the proposed International Geophysical Union" on July 1, 1919.

(2) Citizens of the United States of America engaged in geophysical research or its applications, elected by the Executive Committee of the American Geophysical Union.

(3) Nationals of other countries having the same qualifications, elected by the Executive Committee of the Union; these may not vote or be officers of the Union or of its Sections, or delegates of the Union to International Assemblies or Meetings.

Members in good standing for a total of 15 years shall, following retirement from active professional service because of age and upon advice to the General Secretary, be extended the complete privileges of members without further payment of dues.

(b) Members ex officio--(1) The President of the National Academy of Sciences; the Chairman of the National Research Council; the Chairman of the Section of Geophysics of the National Academy of Sciences; the Chairmen of the following Divisions of the National Research Council: Earth Sciences, Physical Sciences, Chemistry and Chemical Technology, and Biology and Agriculture; and the Director of the Office of International Relations of the National Research Council.

(2) Officers of the International Union of Geodesy and Geophysics and of its Associations who are citizens of the United States of America.

(c) Corresponding Members--Nationals of other countries, outstanding in the field of geophysics, elected by the Executive Committee of the American Geophysical Union; they shall not pay dues but shall enjoy the privileges of Members except that they may not vote or be officers of the Union or of its Sections or delegates of the Union at International Assemblies or Meetings.

(d) Associates--Citizens of the United States of America other than those eligible for regular membership under Article 3, Sections (a) or (b), whose interest in Geophysics is deemed by the Executive Committee of the Union to warrant their election. Associates shall enjoy the privileges of Members except that they may not be officers of the Union or of the Sections, or be delegates of the Union at International Assemblies or Meetings.

(e) Corporation Members--Corporations and other organizations interested in geophysics, elected by the Executive Committee of the Union. The designated representative of each such organization shall enjoy the privileges of a Member.

(f) Student Members--College and university students elected by the Executive Committee. A certificate signed by an officer or professor of the institution attended shall be submitted annually as qualification. The classification of a student member shall terminate after one year of non-student status, and if judged to be qualified by the Executive Committee, the former student shall be an Associate Member on his own written acceptance. Student members shall be privileged to participate in scientific meetings and receive the Transactions of the Union.

Article 4: Sections--The American Geophysical Union shall consist of Sections as follows: (a) Geodesy; (b) Seismology; (c) Meteorology; (d) Terrestrial Magnetism and Electricity; (e) Oceanography; (f) Volcanology, Geochemistry, and Petrology; (g) Hydrology; (h) Tectonophysics.

Members, Corresponding Members, Associates, and Corporation Members shall designate the Section, or Sections, with which they desire to be affiliated. The function of the Sections, in their respective fields, shall be the promotion of the objects of the American Geophysical Union.

Article 5: Officers of the American Geophysical Union--The officers of the American Geophysical Union shall consist of a President, a Vice-President, and a General Secretary, whose terms of office shall expire June 30, 1947, but terms of office effective July 1, 1947, shall be for periods of three years, with the limitation that the President and Vice-President shall not be eligible for immediate reelection; in case any office becomes vacant, the Executive Committee of the Union shall designate a successor in office to complete the term. These officers shall be elected by mail ballot.

There may also be elected, by mail ballot, an Honorary President whose nomination shall be tentatively approved at a meeting of the Executive Committee, followed by a mail ballot of the entire Executive Committee. A confirming vote of three-fourths of those voting shall be required to place the name on the ballot. This office shall be filled only as a special honor for outstanding service to the Union. It shall be for life without payment of dues.

The General Secretary shall act also as Treasurer and shall receive and disburse all dues, grants, and funds otherwise received as authorized by the Executive Committee of the Union; his accounts shall be audited annually by a Committee on Audit.

The Executive Committee of the Union may employ an Executive Secretary, who shall be directly responsible to the General Secretary

Article 6: Officers of Sections--The officers of each Section of the American Geophysical Union shall consist of a President, a Vice-President, and a Secretary, whose eligibility and periods of office shall correspond to those of the Union as indicated under Article 5. These officers shall be elected by mail ballot. In case any office becomes vacant the Executive Committee of the Section concerned shall designate a successor in office to complete the term. The President of each Section shall have the power to appoint, with the right to vote, a representative of the Section to such meetings of the Executive Committee of the Union as he may be unable to attend.

Article 7: Executive Committee--The Executive Committee of the Union shall consist of the President, the Vice-President, and the General Secretary of the Union, and of the President or his designated representative and the Secretary of each Section of the Union, the last past Presidents of the Union and its Sections, the Chairmen of the Standing Committees of the Union; and, in addition, *ex officio*, the Honorary President, the Executive Secretary of the Union, and members *ex officio* as listed in Article 3 (b) of these Statutes.

This Committee shall have charge of all administrative matters of the American Geophysical Union and shall be the representative of the Union in its relations with the National Research Council and the International Union of Geodesy and Geophysics. It shall have the power to delegate to the Officers and to Standing and Special Committees, with power of action and decision, any of its specific functions.

There shall be an Executive Committee of each of the Sections of the Union which shall include at least the President, Vice-President, and the Secretary and the last past President of the Section.

Article 8: Annual Meetings--The American Geophysical Union and its Sections shall meet annually at such time and place as may be chosen by the Executive Committee of the Union.

Article 9: Special Meetings--Special meetings of the American Geophysical Union, of any Section or of any group of Sections, and of any Local or Regional Branch may be called by the respective Presidents with the advice of the respective Executive Committees; notification of such meetings must be communicated promptly to the office of the General Secretary of the Union.

Article 10: Branches of the Union--Local or Regional Branches of the Union may be established on the approval of the Executive Committee of the Union. These Branches shall be organized along the general lines of the Union, shall be responsible to the Executive Committee of the Union, and shall duly report their activities through the General Secretary.

Article 11: Publications--The official publication of the Union shall be the *Transactions of the American Geophysical Union* published under the auspices of the National Research Council of the National Academy of Sciences. Control of matter to be published in the *Transactions* shall rest in an Editorial and Publication Committee composed of at least one Member from each Section, designated by the Executive Committee of the Section which he represents and appointed by the President of the Union. The General Secretary of the Union shall be *ex-officio* Chairman and the Executive Secretary of the Union shall be *ex-officio* Secretary. The Editorial and Publication Committee shall have responsibility (a) of acceptance, editorial revision and condensation, or rejection of any material submitted for publication in the *Transactions* and (b) as regards any special publications subject to the approval of the Executive Committee of the Union.

Non-members of the Union may subscribe to the *Transactions*, and purchase individual copies thereof, as well as other publications of the Union at rates approved by the Executive Committee of the Union.

Article 12: By-Laws--The American Geophysical Union is authorized to enact such By-Laws as may be necessary for the performance of its functions and duties.

Article 13: Amendments--(a) Any Member, Associate, or Corporation Member may propose an amendment to the Statutes. Such proposals shall be considered by the Committee on Statutes and By-Laws and presented to the Executive Committee of the Union with recommendations. Upon approval of the Executive Committee, proposed amendments shall be submitted to the membership for a mail vote. Balloting shall be open for not less than 30 days. A majority of the votes cast shall be required for adoption. Amendments shall be subject to the approval of the National Research Council.

(b) Any Member, Associate, or Corporation Member may propose an amendment to the By-Laws. Such proposal shall be considered by the Committee on Statutes and By-Laws and presented to the Executive Committee of the Union with recommendations. Upon approval of the Executive Committee, proposed amendments shall be published in the *Transactions* not less than 30 days prior to action at a succeeding meeting of the Executive Committee. Action must be completed within a year after publication. Approval by the Executive Committee at this meeting shall constitute adoption of the amendments. An affirmative vote of not less than half the membership of the Executive Committee shall be required for approval.

BY-LAWS

(1) The fiscal year of the American Geophysical Union shall conform to the fiscal year of the National Research Council.

(2) Members of the Union, in classes (a) and (d) of Article 3 of the Statutes, shall pay dues, the amount for each year to be fixed by the Executive Committee of the Union. Members of class (e) shall pay dues of not less than $100 for each calendar year. Any Member or Associate, on payment of not less than $100 at any time, the amount to be fixed by the Executive Committee of the Union, shall be relieved of further payment of dues. Members of class (f) shall pay dues approximating the cost of a volume of the Transactions, the amount for each year to be fixed by the Executive Committee.

(3) Standing Committees shall be as follows: Statutes and By-Laws; Membership; Meetings; Nominations; Budget; Audit; Editorial and Publication.

There shall also be a standing Committee on International Participation consisting of the President, the General Secretary, and the Executive Secretary of the American Geophysical Union and six additional persons (not necessarily AGU members) who are eminent geophysicists with knowledge and background in international organization and cooperation. The Committee shall be appointed at the first meeting of the Executive Committee following each Assembly of the IUGG, and shall serve for a term of three years to include the interval of the next Assembly. The Committee, acting on behalf of the Executive Committee, shall (a) recommend to the Office of International Relations, NRC, the organization of delegations to the Assemblies of the IUGG and to such other international meetings as may be appropriate; (b) review all administrative questions that might or should be raised at, or may be related to, international meetings or assemblies with the view of fully informing our delegations of the implications thereof; (c) advise the NRC Foreign Policy Committee, or the NRC Committee on International Unions, on matters of international science policy relating to geophysical science; and (d) advise the Executive Committee of the AGU of all actions taken or initiated. The Committee shall take full account of the broad interests of geophysical science in the United States, and of the various organizations and agencies involved in geophysical activity.

(4) Special Committees shall be established from time to time, as need arises, to consider special matters approved by the Executive Committee of the Union.

(5) Appointments to Committees of the American Geophysical Union shall be made by the President or President-Elect and appointments shall terminate at the end of the fiscal year for which they are made, unless otherwise specifically designated; no appointment shall extend, however, beyond the term of office of the appointing President or President-Elect.

(6) Meetings of the Union shall be called at least 30 days in advance, and those present at the meeting shall constitute a quorum.

(7) Meetings of the Executive Committee of the Union shall be called by the President at least 15 days in advance and a minimum of 12 shall constitute a quorum.

(8) Final action on matters affecting any Section specifically shall not be taken by the Executive Committee of the Union when that Section is not represented.

(9) Statutes and By-Laws adopted by a Section or Branch shall not conflict with the provisions of the Statutes and By-Laws of the Union.

(10) Matters pertaining solely to a Section and not to the Union as a whole, shall be acted upon by the Section concerned.

(11) No mail ballot of the Union shall be closed until at least 30 days after date of issue.

(12) Officers, designated by the Executive Committee of the Union or the Executive Committee of any of its Sections, to fill uncompleted terms, shall not hold office without election after expiration of the period for which their predecessors were elected.

(13) Removal from the rolls, other than by resignation, of a Member, Corresponding Member, Associate, or Corporation Member of the American Geophysical Union shall be made only upon a three-fourths vote of a quorum of the Executive Committee of the Union; Members, Associates, and Corporation Members who fail to pay dues for two consecutive years shall be reported to the Executive Committee by the General Secretary with recommendation that their names be removed from the Union's rolls.

(14) Under special circumstances and upon request to the General Secretary any Member or Associate may be transferred to an Inactive List of the Union without further payment of dues and without other privileges as Member or Associate but reinstatement may be made upon request and payment of current year's dues.

Reelection of Members and Associates who have been dropped from the rolls by action of the Executive Committee of the Union may be effected only after filing a signed application under the usual procedure for election of Members and Associates.

(15) The Executive Committee of the Union may arrange, either through bequests, special contributions, grants, or other funds of the Union, for awards, medals, honoraria, or certificates of merit to geophysicists in recognition of meritorious work or service in the field of the whole Union or in the field of any of its several Sections, and for scholarships, fellowships, or grants-in-aid to assist worthy candidates in the advancement of geophysical science.

(16) The Executive Committee may appoint Union or Section representatives to other organizations, upon mutual agreement, when such representation may promote coordination and interest in geophysics. The Executive Committee of the Section concerned shall make tentative arrangements for interorganization-relationships and make selections of representatives of the Sections. Arrangements and commitments must be ratified by the Executive Committee of the Union before they are binding on the Union.

(17) The duties of the President shall be those ordinarily appertaining to this office; he shall preside at the meetings of the Executive Committee and at General Meetings of the Union, shall appoint members of Standing and Special Committees; in the absence or disability of the President, the Vice-President shall carry out the duties ordinarily performed by the President. The more important letters, and especially those concerned with policy of the Union, shall be signed by the President or the General Secretary in accordance with rules, precedents, and decisions of the Executive Committee of the Union.

(18) The General Secretary elected by the Union shall be responsible to the Executive Committee of the Union for the general administration of the Union's activities as determined by the Executive Committee of the Union. He shall exercise general supervision over the Executive Secretary, serve without honorarium, receive and disburse funds for the Union in accordance with the instructions of the Executive Committee of the Union, and provide a surety bond, in a sum set by the Executive Committee of the Union and at the expense of the Union, for funds of the Union in his control. He shall sign checks as General Secretary on the account of the American Geophysical Union with a depository approved by the Executive Committee of the Union; in his absence the President, or, in his absence, the Vice-President, of the Union shall sign checks against the account.

(19) The Executive Secretary shall be responsible to the General Secretary and, with the assistance of such clerical help as is necessary, shall perform all executive and other duties as indicated by the General Secretary.

(20) One copy of each issue of (a) the Transactions, (b) any published List of Members and Officers, and (c) any other publication which may be approved for free distribution to the membership by the Executive Committee of the Union, shall be sent to each Member, Associate, and Corporation Member whose annual dues for the calendar year have been paid by July 1; any person or organization newly elected as Member, Associate, or Corporation Member shall be sent without charge one copy of these publications beginning with the calendar year in which elected and for which dues have been paid. Each member on a retired basis, Member ex officio, and Corresponding Member shall be accorded this privilege also. Each Student Member shall receive one copy of each issue of the Transactions for each year of paid membership.

Each person and organization in good standing in any class of membership may purchase any available publication of the Union at one-third discount from printed price-list to non-members. The General Secretary is authorized to establish discounts for sales of publications in quantity.

SPECIAL ANNOUNCEMENTS

Mid-Pacific Regional Meeting to be held in Honolulu, Hawaii, November 15-17, 1955--The Mid-Pacific Region will hold its first three-day meeting in Honolulu, Hawaii, November 15-17, 1955. This group, which bears the name of Geophysical Society of Hawaii, is the regional organization of AGU and a local section of the American Meteorological Society. Those who are interested in the meeting should write directly to John F. Mink, President (P. O. Box 48, Honolulu) or Lawrence E. Eber, Secretary-Treasurer (P. O. Box 3166, Honolulu).

Pacific Northwest Regional Meeting to be held in Portland, Oregon, November 18, 1955--A regional meeting is being planned by the Pacific Northwest Regional Committee and will be held in Portland, Oregon, on November 18, 1955. Those desiring information with regard to the meeting or who would like to present papers should get into touch with the Chairman of the Committee (C. C. McDonald, U. S. Geological Survey, 207 Federal Building, Tacoma 2, Wash.)

Southeastern Regional Meeting to be held in Atlanta, Georgia, December 27-29, 1955--The Ad Hoc Regional Committee for the Southeastern Region under the chairmanship of Werner A. Baum (Department of Meteorology, Florida State University, Tallahassee, Florida) plans to hold a meeting in connection with the annual meeting of the American Association for the Advancement of Science in Atlanta, Georgia, December 27-29, 1955. It is anticipated that the morning sessions of this meeting will be taken up with a broad symposium on the International Geophysical Year 1957-58, and the afternoons will be devoted to programs and papers now being arranged by the Committee. Those who would like to take part in this meeting or who would like to present papers should get into touch with the Chairman as soon as possible.

Plans for Pacific Southwest Regional Meeting--Tentative plans are being made by the Regional Committee under the chairmanship of M. R. Huberty, Professor of Irrigation of the University of California at Los Angeles, to hold a regional meeting probably at the University of California at Los Angeles in late January or early February, 1956. Watch SPECIAL ANNOUNCEMENTS for further information with regard to this meeting or write direct to the Chairman, to the Secretary (R. Corday Counts, Jr., U. S. Weather Bureau, Burlingame, Calif.) of the Regional Committee, or to A. F. Pillsbury (Professor of Irrigation and Soils, University of California, Los Angeles 24, Calif.) who has been designated General Chairman of the Meeting.

Thirty-Seventh Annual Meeting to be held April 30-May 2, 1956--The Thirty-Seventh Annual Meeting will be held in Washington, D. C., April 30 to May 2, 1956 (Monday to Wednesday). This is a first call for titles and abstracts of papers and for suggestions for symposia and other matters relating to the meeting. Address your communications to the office of AGU, to Chairman John N. Adkins of the Committee on Meetings, or to the appropriate Section Secretary [see p. 865 of the Transactions of October, 1954]. Watch SPECIAL ANNOUNCEMENTS in subsequent issues for further information.

Display advertising to be accepted in the Transactions--Under the plan adopted by the Executive Committee in December, 1954, the pages of the Transactions for the first time are open to display advertising germane to geophysics. Persons who are interested in this matter should write to the AGU's new advertising representative (William A. James, 217 Canner St., New Haven 11, Conn.). Attention is also called to the President's letter on the front flyleaf of this issue concerning the recent developments of interest to every member, and to the advertisement on the last page of this issue.

Election of officers of the Union and of the Sections in February, 1956--Attention is called to the fact that the terms of the incumbent elected officers of the Union and of the Sections expire June 30, 1956, and according to a schedule set up [see December, 1946 issue of Transactions, pp. 910-914], the Nominating Committees of the Union and of the Sections are now busily at work selecting the official nominees. If you have ideas with regard to these matters, get into touch with the appropriate Nominating Committee [see Transactions, December, 1954, pt. 2, pp. 125-128, and this issue, pp. 560-561, for names of those on Nominating Committees]. Communications addressed to the office of AGU will also be forwarded appropriately.

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TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

Volume 36 August 1955 Number 4

JOHN PUTNAM MARBLE

John Putnam Marble was born May 30, 1897, in Worcester, Massachusetts. He graduated *cum laude* from Williams College in 1918, having made junior Phi Beta Kappa, and being co-winner of the John Sabin Adriance Prize in Chemistry. He entered the Chemical Warfare Service of the Army in 1918 and, after his discharge early in 1919, completed the school year on studies at Clark University. At the end of the school year he entered the family drysaltery business, where he continued until 1926. He took his Master's Degree in Chemistry at Harvard in 1928 and his doctorate in Analytical Chemistry in 1932 under the guidance of Professor G. P. Baxter.

John Putnam Marble
General Secretary, American Geophysical Union, 1953-1955

It was following the receipt of his doctorate that he really began to find his place and great interests as a scientist. He analyzed radioactive minerals first at the laboratory of the U. S. Geological Survey and, since 1935, at the Smithsonian Institution under the auspices of the Committee for the Measurement of Geologic Time of the National Research Council. In this research he worked closely with Professor Alfred C. Lane. These activities continued to occupy a considerable amount of his time until his death. He became Vice Chairman of the Committee in 1936 and, in 1946, shortly before Professor Lane's death, succeeded him as Chairman. The annual reports that he prepared on behalf of the Committee, including as they did extensive critical international bibliographies, are very important contributions to literature in a field that has been growing rapidly in the last few years. His was a work of love, and he devoted long hours to searches of the literature, compiling his bibliography singlehandedly, and preparing his reports, at the same time carrying on his radioactive research work and diverse activities in such organizations as the American Geophysical Union. His other permanent contributions included about twenty scientific papers mostly bearing on geologic-time analyses, published in a variety of journals, including the American Mineralogist, the Journal of the American Chemical Society, and the American Journal of Science.

During World War II he served as Technical Aide and Special Assistant of the National Defense Research Committee of the Office of Scientific Research and Development.

He was a fellow of the American Association for the Advancement of Science, and at the time of his death was serving as one of the two Council members from the American Geophysical Union. He was a fellow of the Mineralogical Society of America, and of the Geological Society of America, a member of the American Chemical Society, the Electrochemical Society, and the Meteoritical Society. He served the American Geophysical Union in numerous capacities: as member of various administrative and technical committees, for years as Chairman of the Committee on Meetings, and since 1953 as General Secretary. In this last capacity, he was ex officio Chairman of the Editorial and Publication Committee, and took the lead in the development of the new format of the Transactions to be instituted in 1956, and in laying plans for the publication program of AGU in the future. He had served as Secretary-Treasurer of the American Geological Institute shortly after its organization and had represented the Mineralogical Society of America on the Board of Directors for several years.

His interests extended beyond the bounds of science. He enjoyed scientific field trips and many summers in the Adirondack Mountains, and was even happier in the wilds with hammer and lens than in the laboratory. Being interested in education, he served as a Trustee of the Sidwell Friends School of Washington. He was an active member of the Cosmos Club and a member of various other clubs.

Dr. Marble was apparently in reasonably good health and spirits on June 6, the day that he died. He had been in the AGU office until noon, and went to the Cosmos Club for lunch, where the fatal attack occurred. He died the same evening. He is survived by Mrs. Marble, two sons (Richard Almy of Port Antonio, Jamaica, and John Putnam, Jr., at home), two daughters (Mrs. Waldemere Bejnar of Socorro, New Mexico, and Mrs. Robert P. Weis of Harvard, Massachusetts), two sisters (Misses Helen and Sarah), and five grandchildren. His death is a great loss to science and especially to the American Geophysical Union.

Waldo E. Smith

Transactions, American Geophysical Union Volume 36, Number 4 August 1955

A REVIEW OF THE FACTORS AFFECTING THE ACCURACY OF LONG-DISTANCE AND INTERCONTINENTAL GRAVIMETER MEASUREMENTS

G. P. Woollard and W. E. Bonini

Abstract--The problems associated with making gravity connections over large distances with gravimeters are reviewed and discussed. Comparative data are presented as obtained using various types of gravimeters. Discrepancies in results are discussed in terms of their probable sources.

Introduction

Since the adoption of the Potsdam Geodetic Institute absolute gravity base value [KUHNEN and FURTWANGLER, 1906] as the reference value for all international gravity measurements, a major problem has been the determination of the gravity interval between Potsdam and the various national gravity bases. More recently the use of gravity as a means for establishing a more exact shape of the Earth and the undulations of the geoid has emphasized the need for measurements on a world-wide basis having an accuracy of at least one mgal.

Prior to 1939, all long-distance relative gravity measurements were made with pendulum equipment. That even the most careful pendulum measurements gave quite variable results is shown by the differences obtained for the gravity interval between Potsdam and the Copenhagen, Denmark, National gravity base (see Table 1).

Table 1--Value[a] for Danish National Gravity Base, Copenhagen, based on Potsdam 981.2740

Year	Observer	Observed gravity	Difference from adopted value
		gal	mgal
1930	Schmell	981.5544	-3.6
1930	Andersen (1)	981.5580	0
1930	Andersen (2)	981.5638	+5.8
1935	Andersen (1)	981.5593	+1.3
1935	Andersen (2)	981.5595	+1.5
1935	Brockamp (1)	981.5565	-1.7
1935	Brockamp (2)	981.5567	-1.3
Adopted value		981.5580	

[a] Based on HIRVONEN [1948] and SAXOV [1952].

The spread in values here is 5.1 mgals if the 1930 Andersen (2) value is discounted since it disagrees so radically from the others. Presumably, other bases that have not been so well related to Potsdam, and those that have been connected only once have uncertainties in their values of the same order of magnitude indicated by these measurements.

That this conclusion is justified is indicated by the differences observed in the United States between gravimeter values and existing pendulum values. Checks by the writers with gravimeters whose calibration constants had been adjusted to give the best fit to the pendulum data of the U. S. Coast and Geodetic Survey, corrected for base datum shifts [WOOLLARD and Others, 1955], show an average error in the pendulum work of about ± 2.0 mgals. It was, however, noted that for some series of these pendulum observations made during a single field season, the agreement with the gravimeter results was much better and approached ± 1.0 mgal. By way of comparison the average agreement obtained between different sets of gravimeter values in making long-range connections is about ± 0.3 mgal when the same calibration standard is used (see Table 2).

Table 2--Comparative gravity values obtained with different gravity meters relative Washington, D. C., 980.1190 cgs
(Calibration standard used: Australian and British Cambridge pendulum values)

Meter	Year	Observed gravity	Departure from mean
		gal	mgal
Madison, Wisconsin (University of Wisconsin, Science Hall Basement, Room 7)			
Worden 10c	1949	980.3677	-0.8
Worden 41b	1950	.3681	-0.4
		.3684	-0.1
Worden 10e	1950	.3683	-0.2
		.3685	0.0
Worden 10e	1951	.3686	+0.1
		.3681	-0.4
Worden 10e	1952	.3685	0.0
		.3683	-0.2
Frost	1952	.3685	0.0
Worden 142	1952	.3685	0.0
Worden 10f	1953	.3686	+0.1
Worden 147	1953	.3686	+0.1
Worden 10f	1954	.3685	0.0
Worden 147	1954	.3685	0.0
Mean value		980.3685	
Teddington, England (National Physical Laboratory, Meterology Building)			
Worden 10b	1948	981.1961	0.0
Worden 10e	1951	.1960	-0.1
		.1960	-0.1
Frost	1952	.1962	+0.1
Worden 126	1952	.1960	-0.1
Worden 10e	1953	.1961	0.0
Worden 10f	1954	.1964	+0.3
Worden 147	1954	.1966	+0.5
Mean value		981.1961	
Cambridge, England (Pendulum House on grounds of Astronomical Observatory)			
Worden 10b	1948	981.2684	+0.2
Worden 10e	1951	.2681	-0.1
		.2679	-0.3
Frost	1952	.2684	+0.2
Worden 126	1952	.2679	-0.3
Mean value		981.2682	
Port Lyautey, French Morocco (Naval Air Station, old Terminal)			
Worden 10b	1948	979.6531	+1.0
Worden 41b	1950	.6519	-0.2
Worden 10e	1951	.6525	+0.4
Frost	1952	.6505	-1.6
Worden 126	1952	.6525	+0.4
Worden 10f	1954	.6519	-0.2
Worden 147	1954	.6520	-0.1
Mean value		979.6521	

Meter	Year	Observed gravity	Departure from mean
		gal	mgal
Patuxent, Maryland (Naval Air Station, Fleet Air Wing Terminal			
Worden 10a	1948	980.0262	+0.3
Worden 41b	1950	.0258	-0.1
Worden 10e	1950	.0259	0.0
Worden 10e	1951	.0262	+0.3
		.0259	0.0
Frost	1952	.0265	+0.6
Worden 126	1952	.0254	-0.5
Worden 10e	1953	.0261	+0.2
Worden 10f	1954	.0256	-0.3
Worden 147	1954	.0257	-0.2
Mean value		980.0259	
Argentia, Newfoundland (Naval Air Station, Coast Guard Hangar on lower level, Old Fleet Air Wing Terminal)			
Worden 41b	1950	980.8549	+0.3
Worden 10e	1951	.8543	-0.3
		.8546	0.0
Frost	1952	.8565	+1.9
Worden 126	1952	.8545	-0.1
Worden 10e	1953	.8546	0.0
Worden 142	1953	.8549	+0.3
Worden 10f	1954	.8546	0.0
Worden 147	1954	.8548	+0.2
Mean value		980.8546	
Terciera, Azores (Lagens Air Force Base Terminal)			
Worden 10b	1948	980.1760	-0.1
Worden 41b	1950	.1759	-0.2
Worden 10e	1951	.1761	0.0
		.1764	+0.3
Frost	1952	.1770	+0.9
Worden 126	1952	.1762	+0.1
Worden 10e	1953	.1763	+0.2
Worden 10f	1954	.1760	-0.1
Worden 147	1954	.1758	-0.3
Mean value		980.1761	
London, England (U. S. Naval Headquarters, Grosvenor Square)			
Worden 10b	1948	981.2001	0.0
Worden 10e	1951	.2000	-0.1
		.2003	+0.2
Frost	1952	.2002	+0.1
Worden 126	1952	.2001	0.0
Worden 10e	1953	.2001	0.0
Worden 142	1953	.2001	0.0
Worden 10f	1954	.2003	+0.2
Worden 147	1954	.2005	+0.4
Mean value		981.2001	

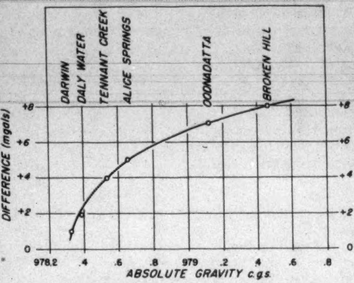

Fig. 1--Difference in gravimeter values, Australia, Worden gravimeter (WHOI) versus oil company gravimeter

However, comparisons of gravimeter results obtained by different groups do not all agree as well as those shown in Table 2. In Figure 1, for example, the difference is shown graphically for results obtained by the writers, and an oil company gravimeter party at the same sites in Australia. Here a difference in linearity of response of the gravimeters, as well as a probable difference in calibration, is indicated. Similarly, Figure 2 shows the difference between values obtained by the writers and STAHL of Expeditions Polaires Francaises (1954) in the same general area. In this case the differences are much smaller and appear to be related primarily to a difference in the calibration of the gravimeters used with random errors of the order of ± 0.3 mgal.

Since gravimeters are now being used extensively for establishing long-distance intercontinental gravity connections, the uncertainties indicated above have given rise to some doubts as to the reliability of these instruments for global gravity measurements. The writers who have been actively engaged in making gravimeter measurements on a world-wide basis for a number of years feel that a review of the problems affecting the accuracy of such measurements and an evaluation of the errors present is, therefore, pertinent at this time.

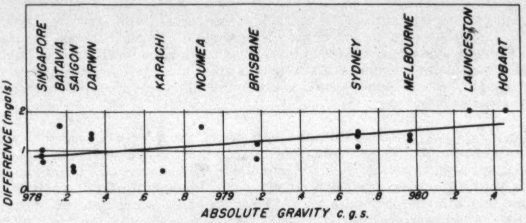

Fig. 2--Difference in gravimeter values, Worden gravimeter (WHOI) relative North American (EPF)

Problems in the use of gravimeters

General remarks--The use of gravimeters for making extended regional gravity measurements covering a thousand miles or more is not new. WOOLLARD [1943] carried out in 1939 a series of gravity measurements at approximately ten-mile intervals on a traverse across North America that covered approximately 4000 mi. The overall accuracy achieved on this traverse from coast to coast was approximately one mgal. This investigation, while not carried out for geodetic purposes, did indicate that gravimeters were suitable for geodetic studies. Also, as the time required for both the observations and the reductions for observed gravity values was so much less than that required with pendulum equipment, it was apparent that gravimeters were better adapted for these studies than pendulums. This was verified by the gravimeter traverse around the world in 1948 by WOOLLARD [1950] on which there was a residual closure of less than one mgal after correcting for instrumental drift and known tares. Although instruments have been improved since then, the problems of carrying out such extended series of measurements are still the same now as then. In the following tabulation, these problems have been divided into groups on the basis of their source: those inherent in the instrument, those representing occasional or special conditions associated with the instrument, and those related to operational or reduction procedures.

- I. A. Sources of inaccuracies inherent in all gravimeters
    - (1) Instrumental stability under varying temperature and pressure conditions
    - (2) Linearity of response to changes in gravity
    - (3) Change in instrument readings with time (drift)
    - (4) Stability recovery rate after resetting
    - (5) Jumps in readings (tares)
    - (6) Accuracy of reading dial assembly
    - (7) Susceptibility to changes in magnetic field strength
  - B. Special situations affecting results occasionally encountered
    - (1) Leaks in barometric pressure compensating element
    - (2) Leaks in thermal insulation
    - (3) Sticking relays
    - (4) Failure of clamp system to rigidly hold elastic system while in transit
    - (5) Sticking of elastic element mass to stops
    - (6) Changes in alignment of instrument level tubes
    - (7) Changes in instrument constants because of dirt in the case
  - C. Special problems related to constant temperature gravimeters
    - (1) Adequate power supply
    - (2) Constant voltage for power supply
    - (3) Sensitivity of thermostat
    - (4) Response of heating element switch relay
- II. Sources of error in operational procedure
  - A. Drift control
  - B. Closures
- III. Sources of error in reductions
  - A. Method of handling drift and closure corrections
  - B. Calibration of instrument

Although gravimeters vary in design, those in general use all share the common principle of having a mass suspended on a mechanical spring system. Depending upon the materials and the design, this elastic system is subject to mechanical distortion by changes in temperature and pressure and, for a considerable period after construction, to a certain amount of non-elastic elongation of the spring system. As a result, the items listed under group I-A above pertain to all instruments in varying degrees.

Instrument stability--Because of the large effects produced by changes in temperature (a mgal or more for a change of 1°F), most instrument are maintained in a heating jacket and thermostated at a temperature well above the diurnal range apt to be encountered. If for any reason, such as low voltage, sticking relays, excessive instrument-air temperature differential, and abnormally high ambient temperature, the temperature is not maintained constant, the readings will be biased by this change in temperature and, as a result, erroneous gravity values will be obtained. Only in the case of one major type of gravimeter, the Norgaard, is an attempt made to correct for changes in temperature on the readings. Only with two gravimeters, the Worden and Atlas, is complete temperature compensation incorporated in the design of the instrument.

Likewise, it is found that all instruments are affected by pressure variations. To overcome this, most gravimeters are mechanically compensated for changes in pressure through the use of a sylphon. Two makes of gravimeters have this effect eliminated by being sealed in a partial vacuum. If a leak develops in either the sylphon or the vaccum bottle seal, the readings will be biased by changes in external pressure.

Linearity--The linearity in the response of a spring to changes in gravity when at the extremes of elongation and compression constitutes one of the major uncertainties and problems connected with the use of high-range gravimeters. With so few reliable pendulum data whereby a high-range gravimeter can be checked over its entire range, it is difficult to evaluate the accuracy of results obtained with these instruments when operating near the ends of the operating scale. It was because of this need for some reliable gravity standard that the writers initiated in 1949 the program to establish a line of precise pendulum measurements extending from Mexico to Alaska.

Drift--As indicated earlier, all gravimeter springs undergo an aging process involving non-elastic deformation (stretch). The rate of stretch, referred to as 'drift rate', appears to be governed by temperature effects with some gravimeters as well as by the age of the spring. Once a spring has become stabilized, 'driftless', it tends to maintain that state with no further elongation. During the transient period of drift, the rate of elongation may vary markedly and even reverse itself for short periods of time. Because of this change in reading values with time, frequent closures are required with all gravimeters that are not driftless. As there are relatively few gravimeters in this class, the time factor is extremely important in most gravimeter operations, and closure must be obtained as frequently as practical so that the observational values can be corrected for this effect.

Recovery rate after resetting--On all single-reading dial instruments, provision is made for extending the operating range by changing the tension in an auxiliary coarse higher tension spring attached to the elastic system. When such a change is made in order to collapse or elongate the spring attached to the reading dial and thus extend the operational range of the instrument, there is usually a period during which the readings show a marked abnormal drift rate. Until a normal drift rate is again resumed, errors in results are apt to result because of this temporary situation. With high-range gravimeters utilizing two reading dials, as the Worden, one reading dial is attached to what would normally be the reset spring, and it is found that oscillating this coarse spring dial back and forth when making large changes in readings permits stability to be achieved in a few minutes rather than hours as observed with most single dial instruments.

Tares--Tares are jumps in readings resulting as a rule from sudden physical shocks to the instrument such as bumping or jarring it. On some instruments, the amount of tare is limited mechanically by stops to a mgal or two; on other instruments tares as large as 150 mgals have been observed. The only safeguard against such effects is careful handling of the instrument, shock mounting during transit, checking the clamping system before moving, and repeating the last previous occupation, if possible, whenever the instrument has suffered any shock. A general safeguard is to establish closures frequently.

Accuracy of reading dial assembly--All gravimeters are subject to an individual type of error associated with mechanical imperfections in the pitch of the screw connecting the spring to the reading dial, the accuracy of the divisional markings on the reading dial, and the centering of the reading dial on the shaft of the screw. While these imperfections are of negligible importance in an instrument having a low range, they do become significant when a single revolution of the dial may represent anything from 100 to 700 mgals. See WOOLLARD and Others [1955]. The amount of error introduced by not correcting for these anomalous effects at various settings of the high-range spring reading dial is shown in Figure 3.

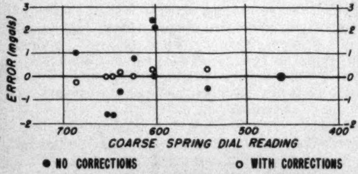

Fig. 3--Observed errors resulting from anomalous response of coarse spring dial (Worden)

Susceptibility to changes in magnetic field--Most gravimeters are constructed of non-magnetic materials, but there are some which are influenced by changes in the Earth's magnetic field. With instruments of this type, corrections have to be applied for such changes in magnetic field strength.

Special situations affecting gravimeter results

The following discussion deals with abnormalities that may go undetected and adversely affect the results obtained.

Leaks in the barometric compensator--Most gravimeters are designed so as to mechanically compensate for changes in atmospheric pressure by having a sylphon which expands and contracts as an aneroid with changes in pressure. If this compensator develops a leak, then the readings will show both a correlation with changes in meteorological conditions and change in elevation. Since this effect is not always too obvious, the only safe procedure to guard against it is to periodically run pressure tank tests on the instrument. The results for such a test conducted by the writers prior to using a high-range North American gravimeter with aeroplane transportation are shown in Figure 4. While no readings are involved while in flight, the recovery rate on the compensator for a plane coming from an elevation of 10,000 feet or more to ground level is important in that it determines how soon after landing a reliable reading can be taken. In the case of the Worden gravimeters this is not as great a problem as with most gravimeters in that the elastic mass is sealed in a partial vacuum and no compensation is thus required. However, if a pressure leak develops in the case, the situation is as serious as with any other gravimeter.

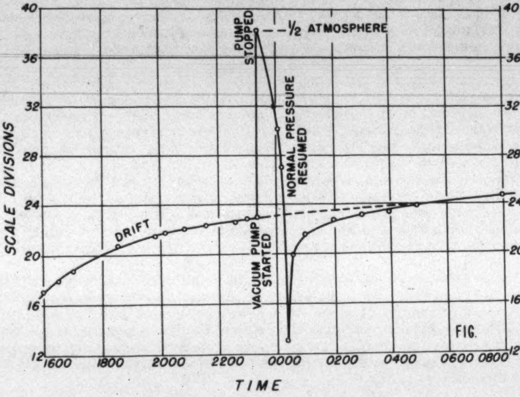

Fig. 4--Pressure response test on North American gravimeter

Leaks in thermal insulation--Leaks of this type are usually caused by cracking of the internal thermos bottle in which the instrument is placed. Such leaks are usually obvious because it is found that the instrument can not be maintained consistently at normal operating temperature, or because very erratic drift rates develop.

Sticking relays--The relays controlling the heating element switch on constant temperature instruments frequently stick because they either become dirty (burned) or because of voltage irregularities. Although most instruments are equipped with pilot lights to indicate whether the relays are closed or open and thus functioning, it is not always obvious when in transit that they are not operating correctly because of vibration effects. Temperature abnormalities under these conditions may not exceed more than a few tenths of a degree. However, when the gravimeter is not in transit, these same relays may stick and the temperature may get several degrees off normal.

With temperature compensated instruments this poses no problem, and usually with the uncompensated instruments inserting new relays will cure the trouble.

Failure of clamp system--On most gravimeters, the elastic system element has sufficient mass to damage the spring system or at least give large changes in reading if left unclamped during transit. A common observational error is to forget to clamp an instrument and thus to introduce a tare in the values. Similarly, if the clamp is not fastened snugly to the elastic system tares will be produced in the results. Clamping can also be overdone and observers have been known to shear off the clamping gear shaft and thus temporarily terminate a survey. So far as the writers are aware, the Worden and Atlas gravimeters are the only two having a mass small enough not to require clamping of the elastic system.

Sticking of elastic element--This effect is peculiar to those elastic elements made of quartz. Because electrostatic charges are built up on the quartz system, the element will adhere to the stops if these charges are not conducted away through the medium and discharged. To accomplish this, the medium is ionized with some radioactive material. However, if the medium is not sufficiently ionized or if dirt gets into the case, the element will tend to stick. In the process of 'thumping' the element loose under such conditions, it frequently happens that a tare is introduced in the results.

Changes in level-bubble alignment--All gravimeters are sensitive to tilt in that the readings are markedly changed when the instrument gets slightly off level. One of the methods of calibrating gravimeters is to observe the reading change produced by different degrees of tilt. If the leveling bubbles affixed to the instrument get out of adjustment, a tare may be produced in the results, or the sensitivity of the instrument may be changed depending upon which direction the instrument is off level with respect to the element. As there are standard tests that should be carried out in the field from time to time for checking the bubble alignment, this effect can be detected and corrected.

Change in instrument constants because of dirt--Although most instruments are sealed so that there is little likelihood of dirt or foreign matter getting in the case, there is usually some leakage of fine dust through the various stuffing boxes. In time, therefore, the mass of the system may be affected sufficiently to give a change in calibration. This becomes a hazard where instruments have to be opened up in the field for repairs or adjustments that cannot be made from outside the case. In general it is best to only open instruments under laboratory conditions, and with some instruments it is recommended that they only be opened by the manufacturer.

Power-supply problems--Power supply constitutes a problem with the constant temperature instruments, particularly if air transport is to be used. Most instruments operate off six volts direct current although some are wired to also operate at 24 volts. In order to carry out international surveys using aeroplane transportation, the power-supply requirements are as follows: (1) a 6- or 24-volt storage battery in safety case meeting the regulations of the Civil Aeronautics Authority; (2) a resistor to reduce voltage from 28 volts as generated on an aeroplane to the 24- or 6-volt level being used with the instrument; (3) a 110-volt AC battery charger; (4) an AC transformer to reduce voltage from the 220-volt level used abroad to 110 volts as needed for the battery charger. In order to keep the voltage level constant and thus avoid sticking of the relays and consequent variations in temperature, the battery is always floated in the heater supply line.

The importance of maintaining temperature in flight depends upon the drift characteristics of the instrument and the measurement being made. With an instrument that has aged sufficiently so that there is no change in readings with time, it is not important to maintain temperature in flight if no measurements are being made except at the flight terminal points. Under these conditions, the only detriment would be the time required for the instrument to reach operating temperature again before observations are resumed. If the instrument does have drift, then it is necessary to maintain constant temperature because of the effect of temperature on the drift rate of the instrument. The writers' experience in carrying out observations with constant temperature instruments using aeroplane transportation on the whole has not been satisfactory for various reasons ranging from objections by the ship's captain to all the equipment required to confiscation of the batteries by officials as a fire hazard.

Temperature regulation problems-- The sensitivity of the thermostats governing the relays operating the heating jacket switches does not constitute a problem except in rare instances where a mercury column thermostat is used and the column becomes divided. In such instances, a tare is developed because of the change in operating temperature. The most common cause of trouble is the relay in the switching circuit. As indicated earlier, dirt, burned points, or voltage irregularities will cause the relays to stick and thus get the instrument off temperature. Replacement of the relays and maintaining a battery in the line as a voltage regulator usually will cure this problem.

Error related to method of reduction

Sources of error in reductions can be related to the method used for determining drift and handling closures. There are three general methods in use for making these corrections.

Method (1)--The drift rates as observed for all observation points reoccupied are plotted and studied as to consistency of rate and possible locations where there are offsets or abnormal rates of drift that could be related to tares. The mean drift rate for such periods when essentially the same drift rate prevailed is then used to determine the drift correction. The residual closure is then distributed on the basis of the tares indicated. As a rule, the drift rate in transit is the same as that observed while stationary or while using a different form of transportation such as a car instead of a plane. Different meters, however, vary in this respect and it is only through experimental testing that the drift stability characteristics of a gravimeter can be determined.

Method (2)--With this system, all changes in values observed at the same observation point, as overnight values or local closures, are closed out and subtracted from the overall closure. The residual is then distributed as drift for the actual hours spent in transit between bases. With this system, tares obtained in transit operations are not recognized.

Method (3)--With this method, the total closure is distributed on the basis of the total number of hours represented by the closure interval; no allowance is made for tares or variations in drift rate during the closure interval.

Experience with various high-range gravimeters has shown that of the three methods, the first gives results that can be most readily reproduced by repeat surveys. The second method works equally well when no tares are obtained while in transit. The third method is the one most subject to potential error. To illustrate this point, closure data are given in Table 3.

Table 3--Closure data for a closed loop run with a Worden gravimeter between Houston, Texas; Washington, D. C.; Madison, Wisconsin; returning to Houston

Place	Date	Time	Large dial	Small dial	Drift data		
					ΔSd	hr	ΔSd/hr
		h m					
Houston	March 28	19 38	229	510.9	...	...	...
Washington	29	05 36	316	489.9	...	...	...
Washington	29	07 13	316	490.2	+0.3	1.5	0.20
Detroit	29	11 20	338	505.6	...	...	...
Detroit	29	14 25	338	505.9	+0.3	3.0	0.10
Madison	29	18 16	344	495.4	...	...	...
Madison	30	14 13	344	499.8	+4.4	20.0	0.22
Houston	30	23 33	229	516.5	+5.6	47.0	0.12
Houston	31	09 00	229	518.8	+2.3	9.5	0.24

It is observed that the drift rate indicated by the individual closures varies from 0.10 scale units per hour to 0.24 scale divisions per hour. Since Earth tide effects have not been allowed for and the reading sensitivity of the instrument in question was about 0.2 mgal per scale division, the above spread in values is not an unreasonable one. The overall closure on Houston for the trip shows only 0.12 scale units per hour drift. Under Method (3) this would be the drift rate used. Under Method (2) the cumulative change in readings while sitting in Washington, Detroit, and Madison (5.3) would be deducted from the Houston closure (5.6), leaving a net change of 0.3 scale unit to be divided by the running time (47-24.5 = 22.5 hr). In this case the result, 0. 0135 units per hour, is an obvious absurdity. There must have been a tare in the survey. If all the above data are plotted as a function of time (Fig. 5), it is seen that this tare occurred while in transit. If it is assumed that the drift rate was constant throughout except as modified by tidal forces, then the magnitude of the tare is found to be of the order of nine scale divisions, about two mgals in this case. By comparing the gravity intervals between the various stops with previous measurements, it was determined that there was a tare as indicated between Madison and Houston.

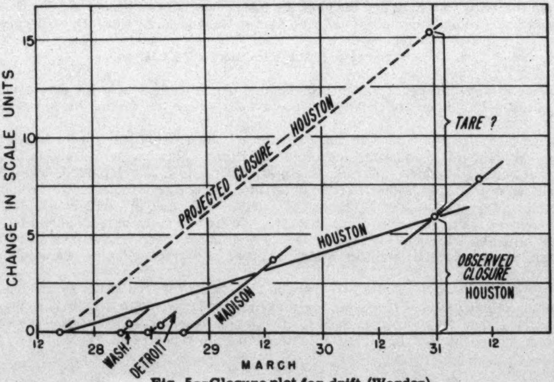

Fig. 5--Closure plot for drift (Worden)

While the above example indicates a constant drift rate throughout, attention should be called to the fact that the drift rate of temperature compensated meters in particular is dependent upon temperature, and it is only so long as the temperature is maintained essentially constant that the drift rate will be constant, Overnight or non-operating drift rates established in a warm office during winter operations may not agree with those based on operating closures. Similarly, when using plane transportation ground drift rates may vary from inflight drift rates, particularly in tropical areas. Therefore, when inspecting drift curves for possible tares, this temperature factor also has to be considered.

Errors related to calibration--Of all the potential sources of error in gravimeter work, calibration is the major one. The sources for an error in calibration are twofold. The standard of calibration used may be in error and the idiosyncrasies of the individual instrument may lead to a misleading calibration. Of the two, the standard adopted is probably the more important. As discussed elsewhere [WOOLLARD and Others, 1955], the standards of calibration in use are varied and it is questionable if, prior to 1949, there was any standard being used that had an accuracy sufficient to permit a calibration good to better than 1 part in 1000. The effects of instrumental idiosynctacies (see Fig. 3) on calibration are fully discussed by WOOLLARD and Others [1955].

Resume on high-range gravimeter observations

Despite the various potential sources of error in using gravimeters for long-range gravity connections, results show that there is very little spread between repeat observations at the same sites. However, there are still uncertainties concerning the values obtained in terms of actual change in gravity because of two factors. One is the uncertainty regarding the linearity of response of the instrument at points near the limit of its operating range. The other is the calibration of the instrument. Up until now there has been no universally accepted gravity standard against which an instrument could be checked for linearity or accuracy of calibration. However, it is hoped that the program of pendulum gravity measurements initiated in 1949 by the writers between Paso de Cortez, Mexico, and Fairbanks, Alaska, will provide such a standard.

Acknowledgments

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NONUNIFORM ROTATION OF THE EARTH AND GEOMAGNETIC DRIFT

W. M. Elsasser and H. Takeuchi

Abstract--The transmission of mechanical forces of the magnetic field through the top layers of the core and into the mantle is analyzed. It is shown that moderate fluctuations of the toroidal field near the boundary of the core are adequate to produce the observed variations in the Earth's rate of rotation. A simple model of the boundary layer of the core is worked out and it is shown that the angular velocity, on going down from the boundary of the core, must first decrease and then increase again, in agreement with the observations on the westward drift and with the dynamo theory.

It has been shown by MUNK and REVELLE [1952] that the irregular fluctuations in the Earth's rate of rotation [BROUWER, 1951] do not, apparently, originate in variations of the atmosphere, ocean, crust, or mantle, but can most readily be explained by means of a variable coupling to the nonuniformly rotating fluid core. According to BULLARD and Others [1950], the mantle is accelerated by electromagnetic stresses arising in the core. The mechanism is put in evidence by the phenomenon of the westward drift of the geomagnetic secular pattern. In Bullard's model the Earth is represented by three concentric spheres in electrical contact with one another, rotating with different angular velocities. The inner two correspond to the core and represent, by means of their differential rotation, the dynamo mechanism which maintains the Earth's field. The outermost sphere, weakly conducting, represents the mantle. It may be shown that under the influence of the electromagnetic torques exerted on it by the inner spheres, the mantle rotates slightly more rapidly than the intermediate sphere. To an observer on the Earth's crust, partaking of the rotation of the mantle, the lag of the intermediate sphere is manifested as the geomagnetic westward drift.

In this paper we study in more detail the transmission of electromagnetic torques from the upper part of the core into the mantle, without making use of a highly specialized model. Our concern will be largely with the variable part of such torques, which can accelerate and decelerate the mantle; we shall endeavor to show that under quite reasonable assumptions the electromagnetic stresses are indeed large enough to account for the observed variations in the rate of rotation of the Earth. It is in the first place clear that the primary forces producing variations in angular velocity are not likely to arise in the immediate vicinity of the boundary of the core; these forces correspond to fluctuations in the hydromagnetic dynamo mechanism which take place at some depth in the core. They must then be transmitted through the top layers of the core into the mantle; we are concerned here with the mechanism of this transmission. This view is in conformity with Bullard's special model. Now if the transmission into the mantle is accomplished by purely mechanical forces, say, some sort of eddy friction, it is clear that in the case of incomplete coupling the upper layers must lag behind the lower layers in which these forces originate. The convective motions in the core will produce a regime where the upper parts rotate more slowly than the lower ones (as is also assumed in the dynamo theory), and this lag should then progressively increase up to the boundary. The same should apply to the frictional transmission of a transient change of torque through the upper core. If the mantle is loosely coupled to the core by mechanical forces, its fluctuations of angular velocity should have the same sign as those of the upper core, but should follow the latter with a lag.

If, on the other hand, the couplings in question are produced by ponderomotive forces of the magnetic field, the fluctuations of angular velocity in the mantle must be contrary in sign to those in the upper part of the core. That is, such forces give rise to differential torques which accelerate the two faces of a layer in opposite directions. The evidence from the geomagnetic drift which indicates that the mantle rotates more rapidly than the top layers of the core may therefore be interpreted in terms of a magnetic coupling mechanism between the two. There is some evidence to the effect that transient variations of the coupling do give rise to opposite accelerations in the mantle and the top of the core. VESTINE [1953] has correlated the geomagnetic secular variations with the fluctuations of the Earth's angular velocity. He studied the migration of the eccentric magnetic dipole through some decades. The eccentric dipole is certainly not a simple measure of the westward drift because there enter into its motion, beside the drift itself, the rates of appearance and disappearance of the various magnetic foci all over the Earth. Nevertheless, if the migration of the dipole shows a definite sign, there exists a strong statistical presumption for regarding this sign as representative of the westward drift. Vestine shows that during the approximate interval 1890-1940 the migration of the dipole is represented by a curve that is quite similar in shape but opposite in sign to the one that depicts the fluctuations in the Earth's rotation. This again indicates that the coupling is magnetic rather than mechanical.

A further corroboration of this view is obtained if we consider the ratio of mechanical to magnetic energy in the top layers of the core. There, for material with density ρ, we have

$$\rho v^2 << \mu H^2/4\pi \;\ldots\ldots\ldots\ldots \quad (1)$$

as may readily be seen if for v we take, say, the linear velocity of the westward drift, 0.03 cm/sec and let H = 2 oersteds (we shall use cgs electromagnetic units in this paper and set the permeability, μ, at unity throughout). This again argues in favor of a preponderance of magnetic effects.

We now compute the force in dynes per cm^2 on the boundary of mantle/core required to account for the observed accelerations of the mantle. The moment of inertia of the Earth is 8.1×10^{44} g - sec^2, of which about 90 pct is contributed by the mantle. We shall take $I = 7.3 \times 10^{44}$ g - sec^2 for the moment of inertia of the mantle. Brouwer's data give irregular variations in the rate of the terrestrial clock which, as a rough upper limit, amount to a cumulative change of, say, $\Delta t = 10$ sec for a period T = 10 years. If we assume a uniform angular acceleration $\dot{\omega}$ to act during T, we have, if $\Delta\phi$ designates the change in azimuth relative to a uniformly rotating Earth

$$\Delta t = \Delta\phi/\omega = \dot{\omega} T^2/2\omega$$

[JEFFREYS, 1952], whence readily

$$\dot{\omega} = 1.5 \times 10^{-20} \text{ sec}^{-2}$$

Now if R designates the radius of the core, the mean lever arm is R/2, and the mean effective area may be taken as $2\pi R^2$, half the surface of the boundary. The force per unit area, the mean tangential stress, is then

$$S = I\dot{\omega}/\pi R^3 = 0.085 \text{ dyne/cm}^2 \;\ldots\ldots\ldots\ldots \quad (2)$$

roughly one-tenth of a cgs unit. The magnetic stress is, dimensionally speaking, of the form H^2 and the observed transfer of angular momentum to or from the mantle can therefore be explained in terms of relatively small fluctuations of the field quantities near the boundary. A somewhat more detailed analysis will now be given.

In polar coordinates, we consider the ϕ-component of the ponderomotive force exerted by the field. This is given by

$$4\pi F_\phi = [\text{curl } H \times H]_\phi = (H_\theta/r \sin\theta)(\partial/\partial\theta)(\sin\theta\, H_\phi) + (H_r/r)(\partial/\partial r)(r H_\phi) \;\ldots \quad (3)$$

We consider first the force on the mantle. It is likely that in the lower part of the mantle the electrical conductivity is larger than in the upper part. We worsen our case if we assume that this conducting layer is only a few hundred kilometers thick. Since the distance from pole to equator along the boundary is 5500 km, we can consider this a thin layer. The first term on the right of (3) is then small compared to the second term and the latter can be simplified, giving

$$4\pi F_\phi \sim H_r\, \partial H_\phi/\partial r \;\ldots\ldots\ldots\ldots \quad (4)$$

Here, H_r is essentially the radial component of the main dipole field, wheras H_ϕ represents the toroidal field which has penetrated upward into the mantle owing to the finite conductivity of the latter. The boundary condition on the toroidal field is that it vanish at the boundary of an insulator [ELSASSER, 1946-1947]. For a stationary toroidal field this leads to the conclusion that the fields in the mantle and core are in the inverse ratio of the conductivities, and the variation of the toroidal field strength with radius in the vicinity of the boundary will be as shown in Figure 1a. A transient fluctuation of the toroidal field, on the other hand, may penetrate into the mantle where it will decrease very rapidly with increasing distance from the boundary, giving rise to a transient condition such as shown in Figure 1b. If we take H_r as constant in the layer in which H_ϕ is appreciable, we can integrate (4) at once over the height of the mantle and find $F_\phi = -H_{ro} H_{\phi o}$, where the subscript

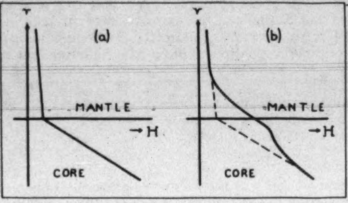

Fig. 1--Radial variation of stationary (a) and transient (b) toroidal field strength in the vicinity of the core-mantle boundary

0 indicates that the fields are to be taken at the boundary. To show that in this way we actually obtain a net torque on the mantle, we specialize the poloidal and toroidal field to be a pure dipole and a pure quadrupole, respectively [ELSASSER, 1946-1947], say

$$H_r = b_r P_1(\cos\theta)$$

$$H_\phi = b_\phi \, \partial P_2(\cos\theta)/\partial\theta$$

where P_1 and P_2 are Legendre functions. Multiplying by the lever arm, $R \sin\theta$, and integrating over the boundary, the torque becomes

$$\tau = (2/5)\, R^3 b_r b_\phi \quad \ldots\ldots (5)$$

Roughly, we obtain the mean stress in dynes per cm^2 on dividing by πR^3 as explained previously in connection with (2). There seems to be no serious difficulty in explaining the numerical value (2) in terms of quite moderate fluctuations of the toroidal field near the boundary, fluctuations which temporarily penetrate into the mantle.

We next consider the top layers of the core. The analysis which we shall use here is very crude, its main merit being that the mathematics can be kept simple. Since it does furnish a meaningful model for the hydromagnetic conditions near the boundary we may expect it to be instructive of the order-of-magnitude relations, although in the details it cannot be expected to be too close to reality. Since the magnetic forces per unit volume of the core are much larger than in the mantle, while the accelerations for core and mantle are equal and opposite, we conclude that we may omit the acceleration terms in a first approximation and compute the balance of forces acting on an element of fluid. We have the Euler equations for stationary flow (assuming the fluid as incompressible)

$$\text{grad}\,(p/\rho) = -2\omega \times v + (4\pi\rho)^{-1}\,\text{curl}\,H \times H + \nu\nabla^2 v \quad \ldots\ldots\ldots (6)$$

where we have omitted the (v grad) v term on account of (1). Here p is the deviation from the equilibrium pressure. The equations for the stationary magnetic field are

$$\text{curl}\,(v \times H) + \nu'\nabla^2 H = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

We leave the detailed interpretation of ν and ν' open, but since the molecular values of the diffusivities are, under the most reasonable assumptions, much too small to lead to a suitable balance of forces, it seems certain that they must be interpreted as eddy diffusivities. We shall return to this point.

We now make the following simplifying assumptions. We write $H + H'$ and $v + v'$ for the field and velocity, respectively. The dashed quantities are the eddying components; it will be assumed that on averaging around a circle of latitude the dashed components have a linear average of zero. We further assume that v has only one stationary component, namely v_ϕ, corresponding to the observed geomagnetic drift. We lump together the averages over the nonlinear terms in H' and v', expressing them in the form of the frictional terms, $\nu\nabla^2 v$ and $\nu'\nabla^2 B$, respectively. This is a somewhat crude assumption which is mainly justified by the fact that it leads to a very simple, workable model. Having thus disposed of the eddy components, we next assume that with respect to the smooth components the layer may be considered as thin. This has two implications. In the first place we take H_r and H_θ as constant throughout the layer; in the second place we neglect $\partial/r\,\partial\theta$ and $\partial/r \sin\theta\,\partial\phi$ operating on the smoothed-out components wherever they appear next to a corresponding term containing $\partial/\partial r$.

We introduce a local cartesian system with the x-axis pointing to the east, the y-axis to the north and the z-axis vertically upward. Then, v_ϕ, H_θ, and H_r become, respectively, v_x, $-H_y$, H_z. With the simplifications enumerated above, (6) reduces to

$$(H_z/4\pi\rho)\,\partial H_x/\partial z^2 + \nu(-\partial^2 v_x/\partial z^2) = 0 \quad \ldots\ldots\ldots\ldots (8)$$

for the zonal component, and

$$\partial\rho/\rho\partial y = -2\omega_z v_x \quad \text{. (9)}$$

$$\partial\rho/\rho\partial z = 2\omega_y v_x - (1/8\pi\rho)\, \partial H_x^2/\partial z \quad \text{. . . . . (10)}$$

for the two other components. Similarly, we obtain from (7) for the zonal component,

$$H_z\, \partial v_x/\partial z + \nu'\, \partial^2 H_x/\partial z^2 = 0 \quad \text{. . . . . (11)}$$

whereas the two other components, with the approximations made, reduce to trivial relations.

We discuss first (9) and (10). These equations show that the fluid will adjust itself so that the pressure gradients balance the Coriolis force. In the case of (10) a magnetic pressure term appears, moreover, in the balance. Numerical estimates readily show that the magnetic term in (10) is not likely to exceed the Coriolis term, and hence (9) and (10) represent pressure gradients of comparable magnitude. The 'geostrophic' balance expressed by these equations is well known and is discussed in standard textbooks of meteorology and oceanography; hence we need not elaborate on it. Clearly, (9) corresponds to the mean meridional pressure gradient in the atmosphere which accompanies its mean west-east circulation. The sign of v_x in (9) is, however, the opposite of that in the atmosphere. A regime of this type is almost certainly unstable and will break up into large eddies corresponding to the major perturbations of the atmosphere. The near-equality of (9) and (10) indicates that the vertical and horizontal extension of our eddies is of comparable magnitude, that is, the macro-turbulence near the core boundary is approximately isotropic. This result is not too surprising, inasmuch as we have not introduced any assumptions that would correspond to stable thermal stratification such as prevails ordinarily in the atmosphere (outside of regions of strong cyclonic vorticity).

The relations (8) and (11) are a system of linear differential equations for H_x and v_x, considering that H_z is assumed constant. We shall henceforth write H and v for H_x and v_x. Values of these quantities and their derivatives at the boundary, z = 0, will be designated by the subscript 0. We have $H_0 = 0$ if we neglect the weak conductivity of the mantle. The boundary condition for v requires a little more discussion. While rigorously it will of course have to be $v_0 = 0$, we cannot at once exclude the possibility that there is a thin sublayer in which v increases very rapidly. If this sublayer is so thin that diffusion of the magnetic field is not impeded by it, in other words that it does not act as a magnetic shield, we would in our present problem have to take for v_0 the value of v at the bottom of the sublayer. Such a layer can, however, develop only when the solid boundary is very smooth. On physical grounds there is a presumption that, instead, the boundary will be rough. The temperature is a few thousand degrees and in spite of the high pressure one is entitled to assume that over periods of geological length diffusion and chemical differentiation will take place. The latter should occur unless mantle and core are in perfect chemical equilibrium from the beginning; small deviations from equilibrium will be enough to lead to recrystallization processes. There should then be excrescences, mountains and valleys, at the boundary. The seismic observations are not precise enough to permit us to discriminate mountains of a few kilometers in height. This is not to say that the scale of roughness is actually of this order; it might be anything below this limit. The gist of this physical argument is that the boundary is more likely to be rough than smooth, and hence the boundary condition $v_0 = 0$ seems appropriate.

We can at once perform a first integration of the equations (8) and (11); with the boundary conditions assumed they become

$$\left.\begin{aligned} a^2H + v' &= v_0' \\ b^2v + H' &= H_0' \end{aligned}\right\} \quad \text{. (12)}$$

where the dash indicates differentiation with respect to z and where the meaning of a and b is obvious. By elimination we readily obtain an equation for H alone and one for v alone. The solution of (12) subject to the boundary condition is then found to be

$$\left.\begin{aligned} aH &= v_0'/a + \alpha e^{\gamma z} + \beta e^{-\gamma z} \\ bv &= H_0'/b - \alpha e^{\gamma z} + \beta e^{-\gamma z}, \end{aligned}\right\} \quad \text{. . . . . (13)}$$

where

$$\left.\begin{aligned} 2\alpha &= H_0'/b - v_0'/a \\ 2\beta &= -H_0'/b - v_0'/a \end{aligned}\right\} \qquad (14)$$

and

$$\gamma = ab = (4\pi\rho\nu\nu')^{-1/2} H_z \qquad (15)$$

A particular solution, whose importance will be explained below, is given by $\alpha = \beta$. This yields

$$H = 4\pi\rho\nu(v_0'/H_z)(1 - \cosh\gamma z) \qquad (16)$$

$$v = (v_0'/\gamma)\sinh\gamma z, \quad H_0' = 0. \qquad (17)$$

At great depth ($z \rightarrow -\infty$), both the field and the velocity increase exponentially in absolute value. We choose the sign of γ so that it agrees with that of H_z, that is, we take the sign of the square root in (15) as positive throughout. Now H_z is negative in the northern hemisphere of the Earth and positive in the southern hemisphere. In order to obtain a westward drift, namely negative v in (17), we must choose the integration constant v_0' positive. This applies to both hemispheres. Then (16) shows that H is positive in the northern hemisphere and negative in the southern hemisphere. These are exactly the signs of the toroidal field which the dynamo theory requires for the deep interior of the core (owing to the nonuniform rotation produced by convection). We see then that H passes monotonically into the toroidal field at greater depth. On the other hand, the nonuniform rotation prevailing in the deep interior corresponds to a progressively more rapid rotation of the inner layers, that is to negative $\partial v/\partial z$, contrary to (17). Hence the curve for v(z) must reverse its slope at some depth and we have the situation depicted in Figure 2.

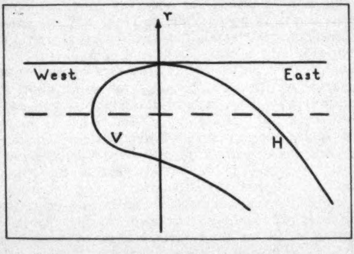

Fig. 2--Radial variation of velocity and field in the upper part of the core

The opposite signs of v and B near the boundary apply, by the way, to all the solutions of (12), not only to the particular solution (16, 17). Clearly, then, our equations of balance, (8) and (11) can no longer apply at great depth where v′ becomes negative. What happens there is that the Coriolis forces exerted by the rising and sinking eddies produce a differential zonal acceleration (which appears as a further term in (8)) in such a way that the balance of forces leads to the pattern shown in the lower part of Figure 2. This means, of course, that at these depths (1) can no longer be valid. We may now identify the boundary layer of the core with the region where v is negative, that is with the region in which the zonal Coriolis acceleration caused by convection is smaller than the terms retained in (8). It must be kept in mind that, owing to the appearance of positive exponentials in our solutions, this is certainly not a boundary layer in the conventional sense.

We shall now give a justification for the specialization of the integration constants used in (16, 17). It will suffice to use an order-of-magnitude argument. We replace $\partial v/\partial z$ by v/D and $\partial H/\partial z$ by H/D. Similarly we write v/D^2 and H/D'^2 for the second derivatives. If these expressions are substituted into (8) and (11), one obtains a system of algebraic equations from which, after some simple calculations, one deduces

$$D/D' = (\nu E/\nu' E')^{1/3} \qquad (18)$$

where E and E′ are the kinetic and magnetic energy densities, respectively. We shall assume $\nu \sim \nu'$ which expresses the fact that the eddy transport and the motions of the magnetic field are closely analogous processes [BATCHELOR, 1950]. This should be the more true here, by Batchelor's arguments, since the eddies in question are secondary phenomena; they are not identical with the deeper primary convective currents. From (1) we have $E/E' \ll 1$, and hence we conclude that the cube root in (18) is a moderately small fraction. If with this result we enter into (14), we find that the second term on the right of these equations outweighs the first term, whence $\alpha \sim \beta$, the desired result.

The preceding dimensional analysis does not give us numerical values for D and D′; we can merely express these in terms of the coefficients of viscosity. We note the relation $DD' = \gamma^{-2}$ where γ is defined by (15); it is obtained by the same procedure as (18). If we assume arbitrarily same value that appears reasonable, say $\gamma^{-1} = 100$ km and set $H_z = 2$ oersteds, we obtain $(\nu\nu')^{1/2} = 2 \times 10^6$. A final question concerns the time required by the boundary layer to adjust to a transient perturbation. For this purpose we must equate (8) to $\partial v_x/\partial t$ and (11) to $\partial H_x/\partial t$. For an order-of-magnitude estimate let us take the first term of (8), which is readily evaluated, and equate it to v_x/T. Then

$$T = 4\pi\rho v_x D'/H_z H_x \quad \ldots\ldots\ldots\ldots \quad (19)$$

If here we take $v_x = 0.03$ cm/sec, $H_z = 2$ oersteds, $H_x = 10$ oersteds, we find

$$T = 5 \times 10^{-4} D'$$

where T is in years and D′ in km. Thus even for large values of D′ the time of adjustment should not exceed several months.

The introduction of eddy diffusivities large enough so that the corresponding frictional terms lead to a balance of forces is the most straightforward device for obtaining equations representing a stationary boundary layer. The simplifications used are, however, somewhat gross and might perhaps be questioned. We have shown elsewhere [TAKEUCHI and ELSASSER, 1955] that a number of our quantitative results can be obtained without an averaging process of the type employed above.

Acknowledgments--The authors are indebted to S. K. Runcorn for a number of valuable and stimulating suggestions. The work covered by this paper was supported by the Geophysics Branch, Office of Naval Research.

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ADDENDUM

Note added March, 1955--We are grateful to Walter Munk for pointing out the importance of showing that the effect of an inclination of the magnetic dipole axis relative to the geographical axis is negligible. Indeed, if the mechanism discussed above is assumed to be symmetrical about the axis of the observed geomagnetic dipole, the torque acting on the mantle has a component in the equatorial plane. This component tends to shift the mantle relative to the axis of rotation, so that the net result, as it appears to an observer fixed on the rotating Earth, will be a displacement of the geographical pole. To compute this we start from the Euler equations for the top,

$$I_1\, d\omega_x/dt - \omega_y\,\omega_z\,(I_2 - I_3) = M_x$$

and two others obtained by cyclic permutation of all the indices. Let the z-axis be the axis of the undisturbed state of uniform rotation. Thus, let $I_1 = I_2$ and write $\Delta I = I_3 - I_1$. We use complex coordinates in the xy plane, letting $\omega_e = \omega_x + i\omega_y$ and $M_e = M_x + iM_y$. Then the Euler equations become

$$I d\omega_e/dt - i\omega_z\,\Delta I\omega_e = M_e \quad \dots\dots\dots\dots \quad (20)$$

$$I d\omega_z/dt = M_z \quad \dots\dots\dots\dots \quad (21)$$

Here we have dropped the indices on I_1 and I_3 as in the approximation required it will not be necessary to distinguish between them. We solve (20) by assuming for ω_z its undisturbed constant value. The torques as written refer to a system of axes fixed in space, but since M_e is fixed in the Earth, we let

$$M_e = M \exp(-i\omega_z t) \quad \dots\dots\dots\dots \quad (22)$$

where we shall consider M as a constant. If we substitute (22) into (20), the solution is

$$\omega_e = \Omega \quad \exp(-i\omega_z t)$$

with

$$-i \;\Omega\,\omega\,(I + \Delta I) = M$$

Here we may neglect ΔI, obtaining

$$\Omega = iM/I\omega_z \quad \dots\dots\dots\dots \quad (23)$$

Now by (21)

$$M/I = (M/M_z)(M_z/I) = (M/M_z)\dot{\omega}_z$$

The physical meaning of the solution obtained is clearly that the rotation is no longer about the z-axis. (The core will, of course, make up for this change of the rotation of the mantle, so that the direction of the total angular momentum in space remains unchanged.) The new axis is inclined relative to the old one by the angle,

$$\phi = \Omega/\omega_z = (M/M_z)\,\dot{\omega}_z/\omega_z^2$$

Numerically, with the value of $\dot{\omega}_z$ given previously and letting $M/M_z = 0.1$ we obtain $\phi = 3 \times 10^{-12}$, corresponding to a displacement of the geographical pole by 0.002 cm. The preceding calculations do not bear out the existence of a slight correlation between a wobble of the pole and a north-south component of the geomagnetic drift, observed by VESTINE [1953]. The correlation seems, however, not pronounced enough to be interpreted conclusively.

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LONG-PERIOD VARIATIONS IN GEOMAGNETIC ACTIVITY

Edwin J. Chernosky

Abstract--The correlation shown by Bartels between annual means of the sunspot number and of the magnetic u figure is markedly improved when means of two longer periods are used. These are the fundamental solar periodicities-- the 11-year sunspot-number and latitude cycle and the 22-year sunspot magnetism cycle. A plot of 11-year running means shows a 22-year variation not too evident in Bartels' annual means, and 22-year running means show a secular low at about 1900, with generally rising activity since then in both the objective u and the subjective C measures. Differences in u and C are ascribed more to evaluations of different regions of the magnetic time-variation spectrum than to inconsistencies of C.

Introduction--Geomagnetic and solar activity have been shown to be generally covariant when annual means of certain of the respective measures have been compared. Correlations of means for shorter intervals such as months or days are generally weaker. One valuable demonstration of the covariation of the geomagnetic u measure and the Wolf sunspot number was provided by BARTELS [1932].

Various investigators have used means for diverse time intervals--some purely terrestrial (as years and days) and some arbitrary (as months). In this paper, pursuant to the idea that magnetic activity is due to solar occurrences, the intervals used are those conforming to the basic solar periodicities of 11 years (the cycle of sunspot number and latitude) and 22 years (that of sunspot magnetism).

Data--The solar data are based on the monthly and annual means of the Zurich (Wolf) daily relative spot number (R) for the whole disk. These data appear regularly in a number of publications. Monthly and annual means of the u figure are given by BARTELS [1932, p. 9; 1952, p. 761]. The international magnetic character figures C, also used here, are available as follows: For 1884-89, BARTELS [1940]; for 1890-1905, VAN DIJK [1938]; for 1890-1937, CHAPMAN and BARTELS [1940]; for 1906-39, VAN DIJK [1924]; and for 1940-53, INTERNATIONAL ASSOCIATION [1948].

Discussion and results--Figure 1 shows averages of C, u, and R for each of the sunspot-number vs latitude cycles. It can be seen that u and R vary together more closely than do C and R. The lowest activity for all these measures is that of Cycle 14. The alternating high-low characteristic of sunspot-number-cycle means is evident also in the u values, but for solar cycles 10-17 only. The five cycles of means of C do not show this alternation; they do, however, follow sunspot-area values. See also Figure 2 of WULF and NICHOLSON [1950].

The annual means of u and of sunspot number give the familiar Bartels graph in Figure 2A, which shows the 11-year variation in magnetic activity. In Figure 2B is shown an original plot of 11-year running means of the two quantities. The 22-year periodicity shown would, of course, support claims of a 22-year period in geomagnetic activity but its existence apparently depends upon the corresponding solar-activity variation.

The 22-year running means smooth out the 22-year variation and show a longer-period variation or trend, with a minimum at about 1905. Available sunspot data indicate that the 1905 minimum was preceded by a similar minimum at about 1815 [CHERNOSKY, 1953]. The close parallelism between solar and magnetic activity shown in the existing data suggests that another magnetic activity minimum occurred then, about a decade or so before the organized observational effort of the Göttingen Magnetic Union began (circa 1836).

C does not have the good annual correspondence with sunspot number that u does (Fig. 3A). The improvement in correlation is very marked, however, in comparisons of the respective 11- and 22-year averages (Fig. 3B and 3C).

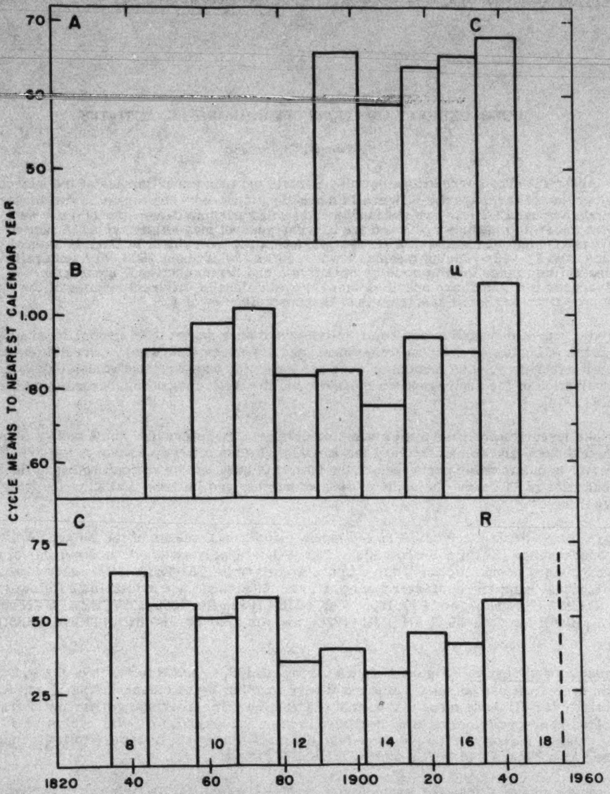

Fig. 1--Variation of C, u, and R shown by cycle means

Of special interest is the general increase in the mean C since the turn of the century, corresponding to solar activity trends. While this increase is not as large relative to the mean as that for the u measure, it is still interesting by virtue of its existence in, and consequent enhancement of, a subjectively-derived measure.

Parameters measured by C and u--It is frequently considered that C and u are comparable measures of magnetic activity and that their monthly or annual averages should vary together. But what parameter does each quantity actually evaluate? In the ultimate analysis it can be said that C is usually an estimate of the (arithmetic) average rate of change of the momentary magnetic intensity for a 24-hour interval, whereas u is a numerical measure of the arithmetic average rate of change of the 24-hr average magnetic intensity (as a function of latitude) for a month or more. For monthly or longer-interval averages u, like C, then measures the average rate of change of magnetic intensity. C and u differ in that C evaluates the shorter- while u evaluates the longer-period changes. The parameter u was originally devised to evaluate long-term means of magnetic storminess from the post perturbation effect.

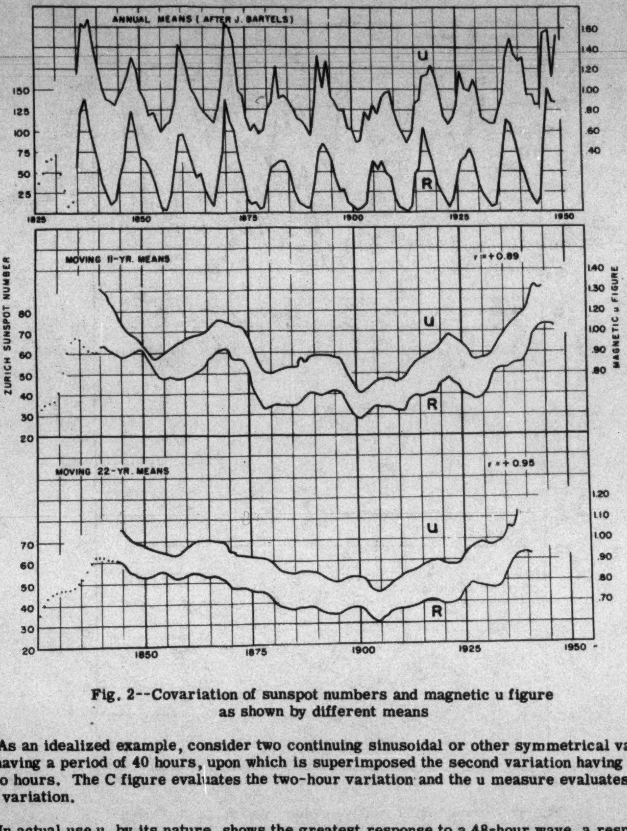

Fig. 2--Covariation of sunspot numbers and magnetic u figure as shown by different means

As an idealized example, consider two continuing sinusoidal or other symmetrical variations, one having a period of 40 hours, upon which is superimposed the second variation having a period of two hours. The C figure evaluates the two-hour variation and the u measure evaluates the 40-hour variation.

In actual use u, by its nature, shows the greatest response to a 48-hour wave, a response which also depends upon the latter's phase relation with the 24-hour interval (Greenwich day). Less response is shown to other periodicities. In general, u evaluates variations for which the equivalent periodicities are in excess of 36 hours, while for C the variations evaluated may range from a few minutes to a few hours. (Although K is a three-hour index, it could evaluate cyclical variations with periods of up to 12 hours.)

In essence, then, C and u evaluate different regions of the magnetic time-variation spectrum. Differences found between C and u could reflect this different spectrum content and would not necessarily imply inconsistency in the C measure. Both C (or K) and u are of importance in the evaluation of magnetic phenomena when properly interpreted. Aspects of the relative value of C and u have been debated by BARTELS [1932, 1948, 1952], VAN DIJK [1935], and HOWE [1950].

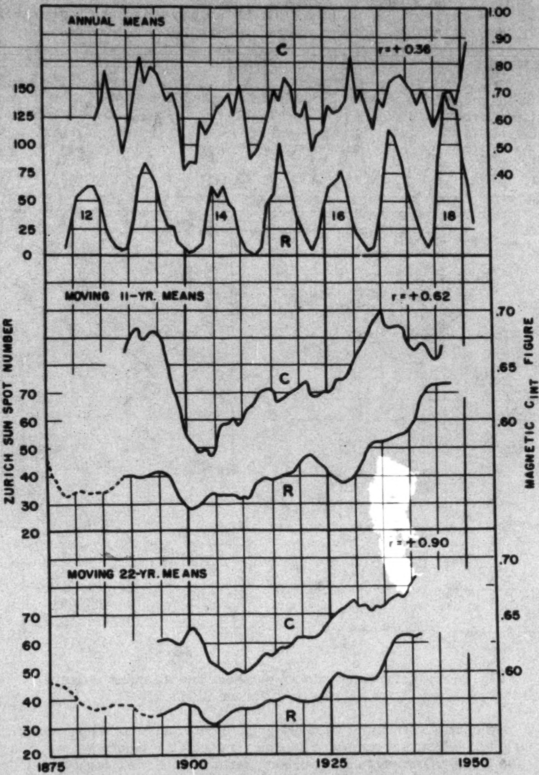

Fig. 3--Covariation of sunspot number and magnetic C figure as shown by different means

Conclusion--Of the nonlocal (multistation) activity measures, only u and C are available for enough years to begin an evaluation for secular trends. Results obtained from these two measures indicate that:

(a) both the C and the u measures correlate better with sunspot number when means for longer intervals are compared;

(b) there is a 22-year variation in the u (or 'low frequency') measure corresponding to similar solar variations;

(c) there was a secular minimum in magnetic activity at the turn of the century;

(d) the C figure, although avowedly an estimate, exhibits this secular trend; and

(e) the existence of secular changes (for example, in the frequency of disturbed days) needs to be kept in mind when intercomparisons of magnetic activity etc., are made for different solar cycles.

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ON THE FORMATION OF BOTTOM WATER IN THE NORWEGIAN BASIN

William G. Metcalf

(Contribution No. 739 from the Woods Hole Oceanographic Institution)

Abstract--The formation of Norwegian Basin bottom water has generally been considered to result from surface cooling during March, April, and early May followed by overturning of the water column to produce homogeneity throughout. Recent data confirm much of the earlier theory but suggest that the cooled surface water may flow toward the bottom along a gently tilted path, and that a homogeneous water column may not play any role in bottom water formation.

The problem of bottom water formation in the Norwegian Basin was considered by NANSEN [1906] and HELLAND-HANSEN and NANSEN [1909]. They believed that bottom water is formed during March, April, and early May in a part of the region between Jan Mayen and Svalbard where there is very little current movement. To a lesser extent, part of the region between Iceland and Jan Mayen was also considered to be of importance in such formation.

According to these investigators, cooling increases the density of the water at the surface causing it to sink. This brings from below to the surface slightly warmer water with a higher salinity. As this process continues, the entire water column is gradually overturned until homogeneity is obtained throughout. Actually, owing to the lateness of the season, the subsurface data presented by these oceanographers do not show this process actively taking place. Surface observations showing the requisite temperature and salinity for bottom water formation were observed during the proper season, but they were not accompanied by subsurface observations. NANSEN [1902] mentions that the sinking of the heavier surface water may not take place at once upon its formation and may be very slow.

Since the time of the above-mentioned papers, the problem has received little attention until recent wintertime observations were made in the central areas of the Norwegian Sea. In the light of the ideas of Nansen and Helland-Hansen, some recent data have been examined for evidence of bottom water formation.

The water below 1500 m in the Norwegian Basin shows a high degree of homogeneity. The recent data show it to have a temperature varying between -0.90 and -1.02°C, the colder temperatures being found in the northern parts of the basin. NANSEN [1906] described it as being between -1.0 and -1.1° in the early years of the century with somewhat colder temperatures present in the north. The recent salinity values of between 34.89 and 34.95 °/oo agree with those reported by Nansen.

At Station B the surface temperature was -0.9° with a salinity of 34.93 °/oo (Table 1). Had the water been homogeneous throughout the column, the early theory would finally have been supported by field data. However, at Station B the shallowest subsurface observation (44 m) showed a temperature of -0.47° and a salinity of 34.88 °/oo. The σ_t at this level was 28.05 compared with a surface σ_t of 28.12. At 1420 m, bottom water conditions were present.

The surface density inversion at both Stations B and C (Table 1) is caused by high surface salinity as well as low temperature. No ice was being formed at the surface at the time, there is no evidence of overturning within the water column, and the water just below the surface is less rather than more saline. It is thus apparent that the overturning mechanism as described by Nansen and Helland-Hansen for increasing the salinity of the water being cooled at the surface is not in operation here. Instead, the surface water of high salinity must have come from the region to the east where surface values of over 35.00 °/oo are evidence of North Atlantic Water (see Station D, Table 1). The low surface temperature is due to local cooling.

In comparing the surface and bottom water characteristics in Station B, two things should be kept in mind. First, the surface temperature was observed only to the nearest tenth of a degree whereas the bottom water temperatures were observed to a hundredth, and second, surface water

Table 1--Data on the bottom water in the Norwegian Basin

Depth	Temperature	Salinity	σ_t	O_2 saturation	Depth	Temperature	Salinity	σ_t	O_2 saturation
m	°C	°/oo		pct	m	°C	°/oo		pct
Station B, March, 1951					Station C, March, 1951				
0	-0.9	34.94	28.12	98	0	-0.9	34.93	28.11	92
44	-0.47	34.88	28.05	71	41	-0.30	34.86	28.03	96
88	-0.48	34.87	28.05	73	84	-0.31	34.86	28.03	88
177	-0.50	34.88	28.05	70	170	-0.34	34.88	28.05	87
268	-0.53	34.86	28.04	71	259	-0.20	34.88	28.04	85
361	-0.22	34.92	28.07	65	351	-0.21	34.92	28.07	86
457	-0.35	34.90	28.06	66	446	-0.36	34.91	28.07	79
555	-0.47	....	....	..	497	-0.43	34.92	28.08	81
745	-0.64	34.90	28.08	74	669	-0.57	34.94	28.11	83
935	-0.80	34.89	28.08	63	843	-0.77	34.91	28.09	83
1130	-0.77	34.92	28.10	66	1200	-0.83	34.91	28.09	83
1420	-0.89	34.93	28.11	70	1568	-0.93	34.92	28.10	80
1720	-0.92	34.92	28.10	74	1949	-0.91	34.92	28.10	80
Station D, March, 1951					Station E, April, 1951				
0	+2.30	35.04	28.00	97	0	+2.9	35.07	27.97	..
46	+2.43	35.06	28.01	95	86	+3.04	35.04	27.93	..
93	....	35.05	....	..	259	....	35.05	....	..
188	+2.41	35.05	28.00	94	440	+0.82	34.95	28.04	..
284	+1.05	34.95	28.02	90	624	-0.03	34.90	28.05	..
380	-0.11	34.89	28.04	84	815	-0.42	34.90	28.07	..
478	-0.29	34.91	28.07	84	1010	-0.64	....	....	..
587	-0.31	34.96	28.11	66	1207	-0.82	34.95	28.12	..
785	-0.57	34.93	28.10	76	1381	....	34.92	....	..
983	-0.70	34.93	28.10	75	1738	-0.93	34.92	28.10	..
1283	-0.87	34.93	28.11	78	2100	-0.95	34.94	28.12	..
1584	-0.94	34.92	28.11	77	2460	-0.96	34.94	28.12	..
1889	-0.95	34.91	28.10	74	2820	-0.95	34.93	28.11	..
Station M, February, 1952									
0	-1.4	34.91	28.11	..					
49	-0.76	34.80	28.00	..					
96	-0.77	34.81	28.01	..					
187	....	34.85	....	..					
352	-0.60	34.87	28.05	..					
428	-0.45	34.90	28.07	..					
498	-0.17	34.89	28.04	..					
560	-0.68	34.88	28.06	..					
650	-0.75	34.88	28.06	..					
830	....	34.90	....	..					
1312	....	34.90	....	..					
1840	-1.02	34.91	28.10	..					
2400	-1.09	34.88	28.07	..					

at -0.9° would be heated adiabatically by 0.06° upon sinking 1500 m. However, it is felt that it is pertinent to point out the close similarity between the surface and bottom water at this station and also at Station C.

The temperature-salinity relationship of each surface observation and also of each observation from below 1500 m from a recent March-April cruise has been plotted in Figure 1. The individual points in the figure represent surface observations and, as expected, show a wide scatter. The deep observations fall into two closely bunched groups shown by the shaded areas in the figure. The area marked North Atlantic includes 11 deep observations from south of the Scotland-Iceland-Greenland Ridge. The area marked Norwegian Sea includes 18 deep observations from the Norwegian Basin. As can be seen, two surface observations, Stations B and C, fall directly within the shaded area representing the Norwegian Basin Bottom Water.

It should be mentioned that the area around Station B and C is one of very little horizontal circulation according to computations based on the circulation theorem, the density structures of the

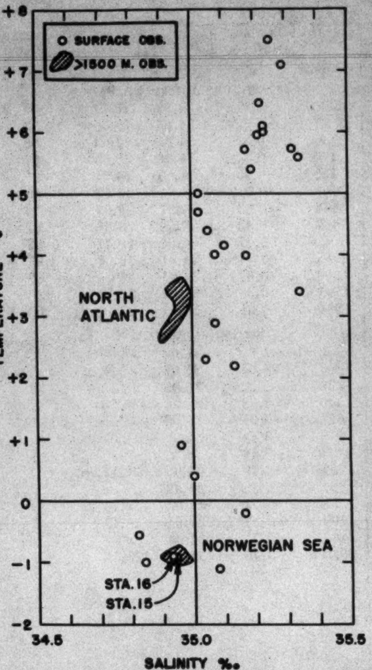

Fig. 1--Temperature-salinity correlation for 1951 cruise

water columns at the two stations and at stations to the northwest and southeast being very similar.

Although only at Stations B and C of the March-April cruise might bottom water formation be suspected on the basis of surface conditions, these two were by no means the only stations showing unstably high surface densities. In a total of 30 stations for which the surface data are available, 23 showed surface density inversions. Of these, 15 stations showed surface densities equal to or exceeding the density of the deepest water sampled at the station.

It is at stations exhibiting high surface densities that according to the early theory one would expect to find a homogeneous water layer extending well down the water column. Yet only rarely was homogeneity found even between the surface and the shallowest subsurface observation, and in these few cases there was no question of bottom water formation taking place, the surface water being either much too fresh or much too warm.

During a January-February cruise the following year, the occurence of surface density inversions was not nearly as wide-spread as it had been during the previous March-April cruise. In 49 stations for which surface data are available, 21 showed such inversions and only one, Station M, had a surface temperature and salinity such that bottom water formation might be suspected (see Table 1). It will be noted that the bottom water at this station, which was in the area north of Jan Mayen, is about 0.1° colder than that observed south of that island.

If it is hypothesized that the frequent occurrence of the density inversions during the March-April cruise is associated with the production at the surface of water destined to sink to a deeper level, then it can be further hypothesized that only the preliminary stages of this process would be in evidence during the January-February cruise if the theory of Helland-Hansen and Nansen is correct as to the season during which such formation takes place. Fitting in with this is the fact that it was at the far northwestern station (Station M), where winter conditions may be presumed to be the most advanced, that surface water was found in February which might conceivably be associated with bottom water formation.

Thus the recent data support Helland-Hansen's and Nansen's theory on bottom water formation except that evidence of the formation of an homogeneous water column is lacking. Even if the supposed overturning were very slow and came about only after a considerable lag as suggested by Nansen, it seems strange that none of the recent observations shows a homogeneous water layer which appears to be related with bottom water formation. This naturally gives rise to the question of whether there is some explanation possible to account for the sinking of this water other than by the gradual overturning within the column.

Figure 2 presents temperature, salinity and σ_t profiles in a northwest-southeast section across the Norwegian Basin between Iceland and Jan Mayen which includes Station B and C. The interpretation of the data given in this figure demonstrates a path along which the cold saline surface water noted at Stations B and C could flow into the bottom water along the isopleths. The exact thickness of such a flow is, of course, not known.

It could be speculated that somewhere in the 75 mi separating Stations B and C a homogeneous water column exists as a result either of vertical flow or overturning as described by Helland-Hansen

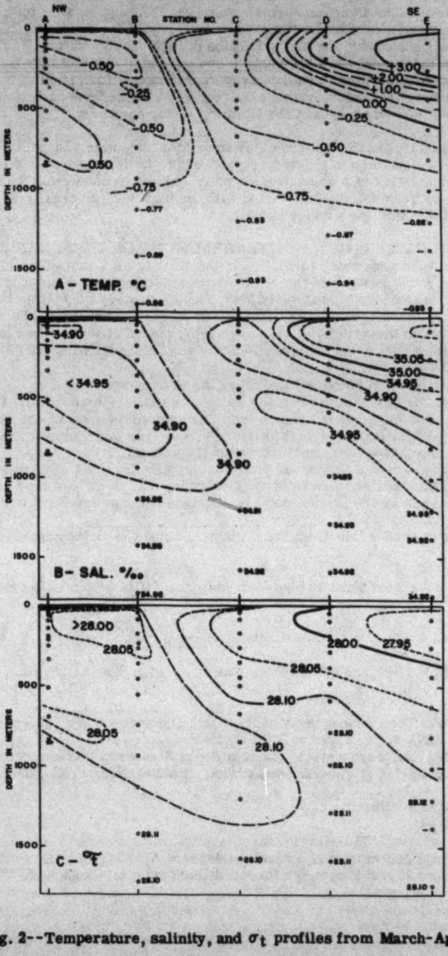

Fig. 2--Temperature, salinity, and σ_t profiles from March-April cruise

and Nansen. However, the particular interspersal of lighter and heavier water layers at those two stations appears to indicate a horizontal component to the flow. In fact, the horizontal component may be by far the dominant one, a point which is obscured by the exaggerated vertical scale used in the profile. It is interesting to note that a flow of water could take place reaching from the surface to a depth of 1500 m between Stations B and C along a path tilted only 0.6° from the horizontal.

Although shown in the figure as a continuous flow from the surface to deeper than 1500 m, such a flow may very well be a discontinuous one interrupted from time to time as conditions at the surface become unfavorable for the production of high density water. For example, a period of high air temperatures would halt the surface cooling which is necessary for bottom water production, and strong surface winds would destroy by mixing any formation of a high density surface layer. In other words, the picture shown may represent the general pattern by which water from the surface reaches the bottom but not the situation at any one time.

Thus it appears that active bottom water formation was observed, and a means by which this water travels from the surface to the deeper portions of the Norwegian Basin is indicated. At no point is there any indication of a homogeneous water column in connection with this formation, and the relatively high surface salinity associated with the high surface density is definitely not the result of overturning within the water column.

Summary--(1) NANSEN [1902, 1906] and HELLAND-HANSEN and NANSEN [1909] advanced the theory concerning bottom water formation in the Norwegian Basin which maintained that this water (a) is formed at the surface in the region between Svalbard and Iceland; (b) is formed by surface cooling during March, April, and early May; and (c) reaches the bottom by means of the gradual overturning of the water column which produces homogeneity throughout. This overturning is also the mechanism by which the salinity of the water being cooled at the surface is raised.

(2) Recent winter data from the area indicate that oceanographic conditions have changed very little in the past 50 years.

(3) These data confirm points (a) and (b) of the earlier theory.

(4) These data suggest that the surface water of relatively high salinity found in the area where bottom water formation is suspected comes from the area to the east where North Atlantic Water with salinities above 35.00 °/oo is present at the surface rather than being brought to the surface from below.

(5) There is no evidence for overturn within the column.

(6) It is suggested that a flow along isopycnal surface is the means by which the relatively heavy water found at the surface moves to the deeper layers. This flow may be a discontinuous one interrupted on occasions as the conditions at the surface become unfavorable for the increase in surface density.

(7) The angle of such a flow from the horizontal cannot be determined from the data, but it may be very slight.

Acknowledgment--This work was sponsored by the Office of Naval Research under Contract N6onr-27701.

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THE CIRCULATION OVER THE CONTINENTAL SHELF SOUTH OF CAPE HATTERAS

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(Contribution No. 788 from the Woods Hole Oceanographic Institution)

Abstract--South of Cape Hatteras, a southerly-flowing coastal current, such as is common to the northward, is a transient affair. Such a current, when present, is restricted to a very narrow portion of the continental shelf. The dynamic pressure gradient resulting from the combined effect of the runoff and the cross-shelf thermal gradient together with the prevailing wind and the frictional drag of the Florida Current provides for a northeasterly drift over a broad part of the Carolina continental shelf.

The waters of the continental shelf of the United States south of Cape Hatteras (Fig. 1) have received, until recently, exceedingly little attention compared with the shallow and slope waters to the north. Prior to 1948 the oceanographic data from this region comprised occasional observations by Bigelow, one section by ISELIN [1936], and current measurements by the U. S. Coast and Geodetic Survey alluded to by RUDE [1922] and reported by HAIGHT [1942].

The only discussion of the oceanography of the region lies in a recent summary by MARSHALL [1951], but that deals mostly with the waters of the sounds. Toumey in the Geological Survey of South Carolina for 1848 described 'an eddy current which washes the coast southwardly' [GULLIVER, 1899]. Backset eddies driven by the Florida Current have been considered as responsible for the cuspate form of the coast line by ABBE [1895], GULLIVER [1899], DAVIS [1912], and SHEPARD [1948]. RUDE [1922], on the basis of current measurements in the winter of 1915-16 and 1916-17, does not accept the theory of backset eddies. He found superimposed on the rotary tidal current 'a set with the local wind prevailing at the time of observation.' PARR [1933] noted the winter temperature barrier which occurs at Cape Hatteras. PIERCE [1953] demonstrated that the distribution of chaetognaths was directly related to the water masses in the area.

One of the characteristic features of the hydrography of continental shelf waters is a dynamic coastal current induced by the addition of fresh river runoff water at the coast. The southerly-flowing current along the eastern seaboard of the United States north of Cape Hatteras is an example. Part of this current manifests itself near the coast as a slow drift of three to 20 mi/day [MILLER, 1952], but most of the transport is near the 100-fm contour where it does not have to overcome bottom friction.

It has become evident from recently collected data south of Cape Hatteras that a southerly-flowing coastal current in that region does not always exist. Certainly, one can never exist along the 100-fm line inasmuch as the Florida Current lies just a few miles from the 100-fm line, and waters over the edge of the shelf are subject to the frictional drag of this great stream.

There appear to be several reasons why a dynamic coastal current is a transient affair in this region:

(1) Raleigh Bay and Onslow Bay receive no regular contribution of freshened water or southerly-flowing water from north of Cape Hatteras. Hence there is no continuity with the waters north of Cape Hatteras. As will be noted in (2) below, the fresh-water contribution from the rivers is small and mixed with sea water. If the runoff into this region were comparable to that of Chesapeake Bay, a coastal current would be assured of a healthy inception.

(2) River water contributions per unit length of coast line are on the average less than one half as great as for any other section of the coast (Table 1), It is apparent that the runoff per unit area for the Carolina region is not, on the average, significantly less than for the other regions, but the runoff per unit length of coast line between Cape Hatteras and the South Carolina border, that is, of the Pamlico, Neuse, and Cape Fear River basins, is very small, being 1.9 m^3/sec km, as compared with an average of 5.2 m^3/sec km for all the other sections of this coast. Further, the effluent from the rivers becomes well mixed with sea water in the estuaries and sounds so that the water entering the sea through the inlets is no longer very fresh. (Mixing in the Cape Fear River may not be as complete as in the other estuaries in the region.) For instance, salinities observed at Hatteras and Ocracoke Inlets ranged from 28.5 to 35.5 $^o/_{oo}$ [ROELOFS and BUMPUS, 1953]; at Beau-

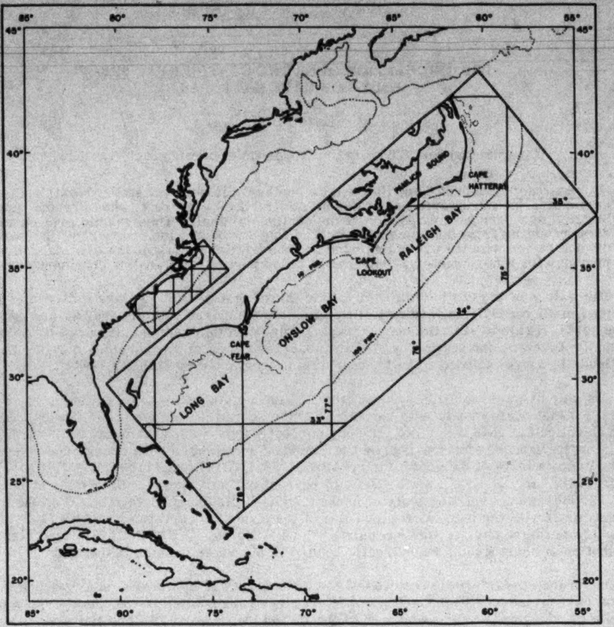


Fig. 1--Chart of east coast of the United States with inset indicating area under discussion

fort Inlet from 18 to $35.4\,^{0}/_{00}$ [SUTCLIFFE, 1951], but generally greater than $32\,^{0}/_{00}$. Lower salinities are always found at the mouths of the Hudson River, Delaware Bay, and Chesapeake Bay. As a result the salinity gradient is greater next to the coast off the northern shores than in Raleigh or Onslow Bays.

(3) The temperature gradient across the continental shelf during the winter months is more than sufficient to counteract the salinity effect on the pressure gradient during periods of average runoff, thus dynamically providing for a northerly set to the coastal waters.

(4) Owing to the geography of the coast line the southwesterly wind, which is the prevailing wind during many months of the year, blows parallel to the general direction of the coast south of Cape Hatteras, whereas from Hatteras to New York it is an offshore wind. This wind with a relatively long fetch at Long, Onslow, and Raleigh Bays serves to retard or deflect offshore any south-flowing coastal current.

(5) Further, this southwest wind will pile up water on the south sides of the capes creating an hydraulic current which tends to flow offshore over the projecting bars. This hydraulic current will deflect offshore any southerly flowing coastal current approaching the cape on the lee side, and, through turbulence, will mix it with more saline water, thus preventing augmentation of the current from one river mouth to the next. (This opposition of currents at the cape tips may indeed provide the mechanism which helps to maintain the capes, inasmuch as the velocities may be reduced there and the heavier elements of the sediment loads dropped.)

(6) Finally, the proximate Florida Current produces a frictional drag on much of the water over the continental shelf, which drag a coastal current must overcome.

Table 1--Mean runoff data for several drainage basins along Atlantic Seaboard of the United States

Drainage basin	Runoff[a]	Drainage area[b]	Runoff	Coast-line	Runoff
	m^3/sec km^2	km^2	m^3/sec	km	m^3/sec km
Hudson River	0.017	34618	588	135	4.35
Delaware River	0.019	36001	684	136	5.02
Chesapeake Bay	0.013	173979	2261	244	9.3
Albermarle Sound	0.012	43019	516	67	7.7
Pamlico to Cape Fear River	0.011	61981	682	352	1.9
Peedee, Savannah and Altamaha Rivers	0.012	198430	2380	485	4.9

[a] Based on U. S. Geological Survey Water-Supply Papers 1171 and 1172.
[b] Includes both gaged and ungaged areas.

Thus it appears that a southerly-flowing coastal current will not prevail during the winter months unless the runoff is exceptionally great. At other times of the year such a current will depend primarily on the amount of runoff and secondarily on the wind direction, force, and duration. The following observations are presenced in support of this hypothesis.

Runoff data--The runoff for the period October, 1947, to September, 1953, and the occasions when the cruises were made to collect the hydrographic data are shown in Figure 2. We see that immediately prior to Reliance Cruises 4 and 6 the runoff had been four times greater than the mean but was diminishing rapidly. Prior to Caryn Cruise 7 and Albatross III Cruises 18-19 the runoff had been well above the mean for several months but had dropped to near mean values. Prior to Albatross III Cruises 30 and 32 runoff averaged less than the mean for several months. Prior to Caryn Cruise 64 runoff had been twice the mean but had since diminished. These runoff trends are reflected in the salinity distribution over the continental shelf and hence contribute to the distribution of the dynamic pressure gradient.

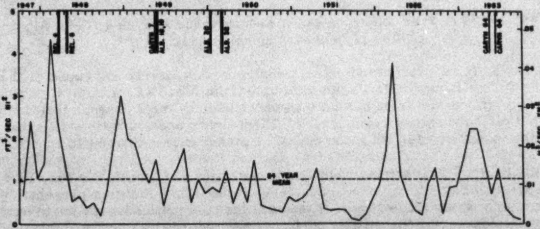


Fig. 2--Runoff for the period October, 1947, to September, 1953, from Pamlico, Neuse, and Cape Fear River basins, [U. S. GEOLOGICAL SURVEY [1952, 1953] and data kindly furnished by the District Engineer in North Carolina

Drift bottles--Two sets of drift bottles (with and without drags) were released in the North Carolina area, one set in January and the other in February and early March, 1950, Albatross III Cruises 30 and 32.

The first set comprised 816 bottles released at 51 positions, 16 bottles at each position. The 46 recoveries from 17 of the positions are shown in Figure 3. The second set comprised 490 bottles released at 49 stations, ten at each station. The 24 returns from 15 positions are shown in Figure 4.

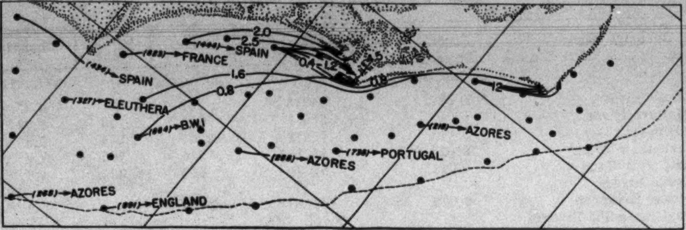


Fig. 3--Routes of drift bottles released January 9-13, 1950, Albatross III, Cruise 30; numbers indicate drift in miles per day; numbers in parentheses indicate days of drift

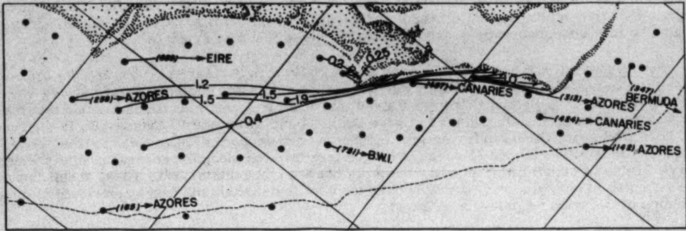


Fig. 4--Routes of drift bottles released February 25 - March 4, 1950, Albatross III Cruise 32; numbers as noted under Fig. 3

These drift-bottle recoveries indicate a definite north-easterly movement of the surface coastal waters during January-March, amounting to from 0.2 to 12 mi/day. It is also apparent from the foreign returns and from the bottles conspicuous by their absence that the movement tends somewhat offshore rather than onshore. These drifts are compatible with that indicated by the hydrographic conditions for the same period, a period of less than mean runoff.

Two of MILLER's [1952] bottles, launched in the offing of Cape May in May 1951, stranded on the shores of Raleigh Bay, having moved southerly around Cape Hatteras presumably during the five days of easterly winds, June 15-20. These are the only bottles on record to have rounded the Cape in that direction or, for that matter, to have been recorded as moving southerly in this region.

Temperature, salinity, and density distribution--The temperature and salinity data were collected in the course of eight cruises: March 19-25, 1948, Reliance, Cruise 4; April 26-May 1, 1948, Reliance, Cruise 6; May 13-15, 1949, Caryn, Cruise 7; May 20-25, 1949, Albatross III, Cruises 18-19; January 8-13, 1950, Albatross III, Cruise 30; February 25-March 4, 1950, Albatross III, Cruise 32; May 13, 1953, Caryn, Cruise 64; and June 9-10, 1953, Caryn, Cruise 64.

Typical sections across Onslow Bay, Figures 5, 7, 9, 11, 13, 15, 17, and 18, diagram the distribution of temperature, salinity, and density in profile. The distribution of these same properties at the surface in Long, Onslow, and Raleigh Bays is illustrated in Figures 6, 8, 10, 12, 14, and 16. From the two sets of figures a general idea of the hydrography of the area may be obtained. The conditions peculiar to the several times of observation are summarized below.

January 8-13, 1950; Albatross III Cruise 30 (Fig. 5 and 6)--Strong horizontal temperature gradients but minimal vertical temperature gradients were characteristic of the shelf waters in January,

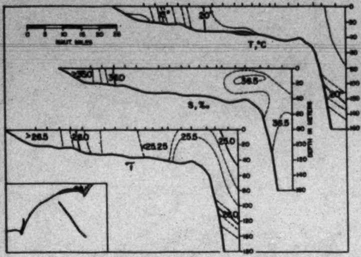
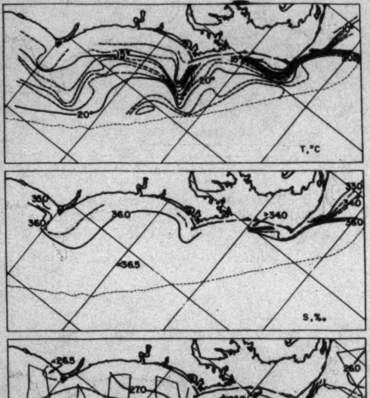


Fig. 5--Distribution of temperature, salinity, and density across a typical section in Onslow Bay, January, 1950, Albatross III, Cruise 30


15°
20°
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35.0
36.0
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>34.0
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<36.5
S,‰
<26.5
27.0
26.0
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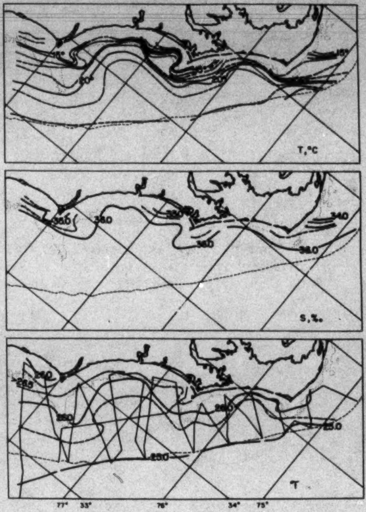
26.0
77° 33°
76°
34° 75°

Fig. 8--Distribution of surface temperature, salinity, and density on North Carolina shelf, February, 1950, Albatross III, Cruise 32


15°
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26.5
26.0
26.0
25.0
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77° 33°
76°
34° 75°

Fig. 6--Distribution of surface temperature, salinity, and density on North Carolina shelf, January, 1950, Albatross III, Cruise 30

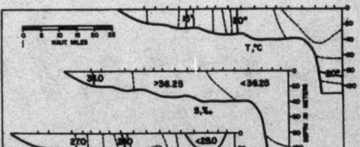


Fig. 7--Distribution of temperature, salinity, and density across a typical section in Onslow Bay, February, 1950, Albatross III, Cruise 32

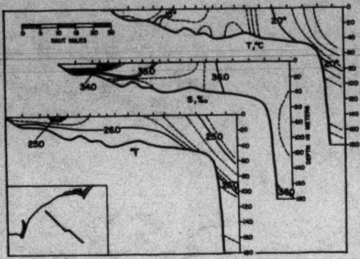
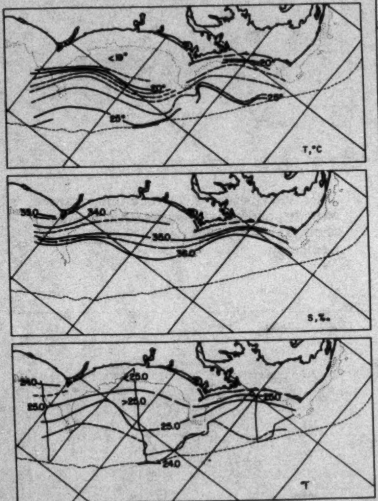


Fig. 9--Distribution of temperature, salinity, and density across a typical section in Onslow Bay, March, 1948, Reliance, Cruise 4


<19°
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T, °C
34.0
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36.0
S, ‰
24.0
<25.0
>25.0
25.0
°T
77°
33°
76°
34°
75°

Fig. 12--Distribution of surface temperature, salinity, and density on North Carolina shelf, April, 1948, Reliance, Cruise 6

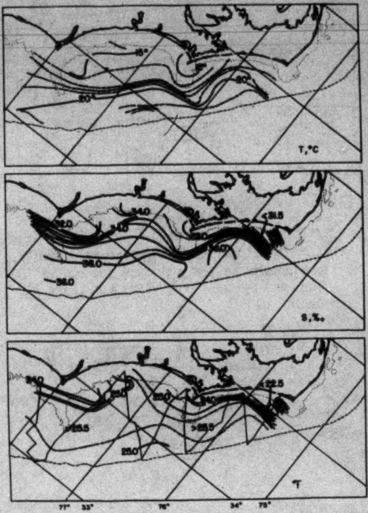

15°
20°
T, °C
32.0
34.0
31.5
36.0
S, ‰
24.0
<22.5
>25.5
25.0
°T
77°
33°
76°
34°
75°

Fig. 10--Distribution of surface temperature, salinity, and density on North Carolina shelf, March, 1948, Reliance, Cruise 4

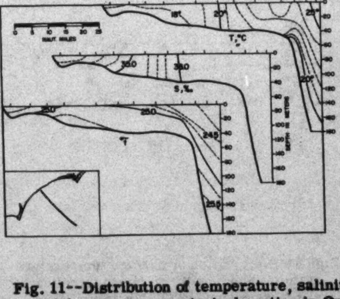


Fig. 11--Distribution of temperature, salinity and density across a typical section in Onslow Bay, April, 1948, Reliance, Cruise 6

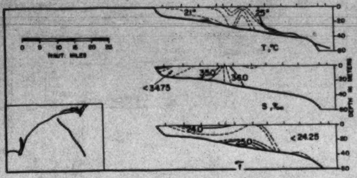
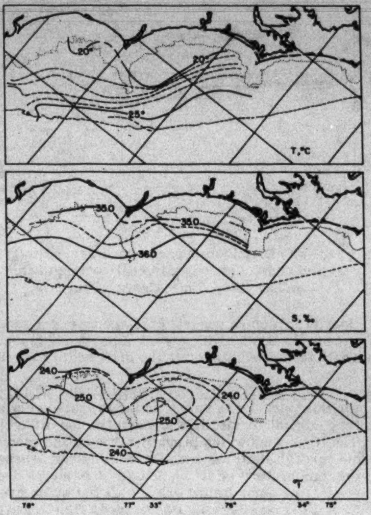


Fig. 13--Distribution of temperature, salinity, and density across a typical section in Onslow Bay, May, 1949, Caryn, Cruise 7


20°
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T, °C
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36.0
S, ‰
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25.0
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σT
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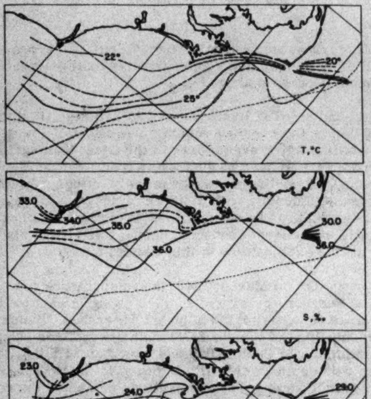
77°
33°
76°
34°
75°

Fig. 14--Distribution of surface temperature, salinity, and density on North Carolina shelf, May, 1949, Caryn, Cruise 7


22°
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T, °C
33.0
34.0
35.0
36.0
30.0
36.0
S, ‰
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24.0
23.0
>24.75
25.0
24.0
24.0
σT
77°
33°
76°
34°
75°

Fig. 16--Distribution of surface temperature, salinity, and density on North Carolina shelf, May, 1949, Albatross III, Cruises 18-19.

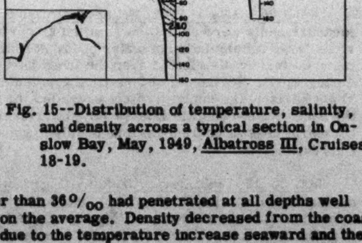

Fig. 15--Distribution of temperature, salinity, and density across a typical section in Onslow Bay, May, 1949, Albatross III, Cruises 18-19.

1950. The salinity distribution tended to be similar to the thermal structure although the relatively small runoff during the preceding weeks accounts for the absence of lowered salinity next to the coast. Water of salinity greater than 36 $^0/_{00}$ had penetrated at all depths well across the shelf to within ten miles of the coast on the average. Density decreased from the coast seaward in Onslow and Raleigh Bays. This was due to the temperature increase seaward and the insufficiency of freshened water next to the coast to counteract the temperature effect. Hence the

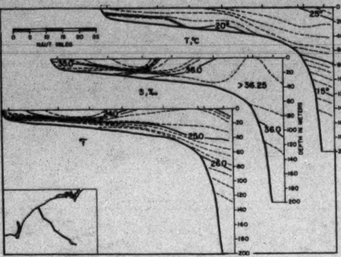

Fig. 17--Distribution of temperature, salinity, and density across a typical section in Onslow Bay, May, 1953, Caryn, Cruise 64

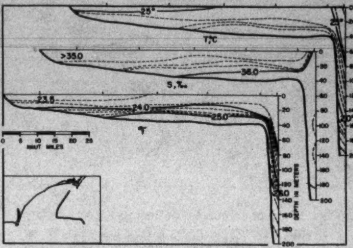

Fig. 18--Distribution of temperature, salinity, and density across a typical section in Onslow Bay, June, 1953, Caryn, Cruise 64

density structure suggests the absence of a countercurrent and a slow northerly drift all across the shelf. South of Cape Fear a southerly coastal drift is indicated. The northerly drift over the shelf was substantiated in the drift bottle experiment described above.

February 1950; Albatross III Cruise 32 (Fig. 7 and 8)--The temperature and salinity structure for this period was very similar to that observed during the previous month. The effect of lower than normal runoff allowed the intrusion of highly saline water even closer to the coast than earlier. The NNW wind which prevailed during the month appears to have pushed water from Pamlico Sound out through Hatteras and Ocracoke Inlets, freshening and cooling the water in their offings. Again the temperature effect on density produced a decrease in density with distance offshore at all depths, suggesting a northward drift of all the water over the shelf. The nascent coastal current south of Cape Fear was less well developed. The drift bottle experiment conducted during this cruise also gave supporting evidence for a northerly drift of all the shelf waters in this region.

March 19-25, 1948; Reliance Cruise 4 (Fig. 9 and 10)--In March, 1948, the temperature and salinity distribution differed from the January and February conditions of 1950 owing in part to the vernal warming, but chiefly to the preceding large runoff from the adjacent watershed. Water of salinity greater than 36 ‰ lay over the outer one-third of the shelf, the inner two-thirds being occupied by effluent water of less than 33.5 ‰ minimum in Onslow Bay and less than 31.5 ‰ minimum in Raleigh Bay. Temperature increased with depth as did salinity owing to the flooding of the colder effluent out over warmer more saline shelf water. These conditions combined to produce a slight vertical density gradient, maximum densities at all depths occurring over the central part of the shelf, with lowered densities offshore and still lower densitites inshore. These dynamic conditions should produce a weak southerly coastal current over the inner part of the shelf. The winds were predominantly NE during the preceding month and a half. The SW wind blowing at the time the observations were made in the northern part of Raleigh Bay served to move a thin layer of the Pamlico Sound water from Hatteras and Ocracoke Inlets offshore over more saline water.

April 26 - May 1, 1948; Reliance Cruise 6 (Fig. 11 and 12)--Although the observed salinity measurements were not as low in April as during the preceding month it is apparent that the previous large accumulation of water of low salinity and the continued greater than mean runoff was more uniformly distributed over the inner part of the shelf because of the prevailing southwest wind during April. Horizontal and vertical gradients were weaker than during the previous month. A slight horizontal density gradient prevailed throughout the area with the maximum at all depths over the center of the shelf in Onslow Bay, but closer inshore in Raleigh Bay. This indicates a weak southerly coastal current inshore of this low and a northerly drift offshore parallel to the Florida Current.

May 13-15, 1949; Caryn Cruise 7 (Fig. 13 and 14)--No observations were made in Raleigh Bay during Caryn Cruise 7 nor were those in Onslow Bay well distributed. They do serve, however, to demonstrate the tendency at this time for a thermocline to develop, although it was very weak over the inner one-third of the shelf. The intrusion of considerable runoff augmented the stability, although the vertical salinity gradient was weak. There appears from the density structure to be a weak southerly current although there may be a weaker northerly current inshore if it. The prevailing SW wind during the preceding month may have served to move the coastal current and attendant freshened water slightly offshore. The outer one-third of the shelf was occupied by virtually isothermal, isohaline Florida Current water.

May 20-25, 1949; Albatross III Cruises 18 and 19 (Fig. 15 and 16)--Little change in the vertical structure since the cruise a few days earlier is evidenced in these data. During this cruise, with somewhat better coverage of the area than, *Caryn* Cruise 7, Raleigh Bay was virtually flooded with highly saline water, $S > 36^{0}/_{00}$, whereas freshened water, $S < 35\ ^{0}/_{00}$, tended offshore in the southern part of Onslow Bay. A density high occurred over the central part of Onslow Bay with an appreciable gradient toward the shore, especially in the northern part of Long Bay. This suggests the development of a moderate southerly-flowing coastal current commencing in Onslow Bay, being augmented in Long Bay by the Cape Fear River.

May 13, 1953; Caryn Cruise 64 (Fig. 17)--A single section across the center of Onslow Bay provides data for May, 1953. The waters are slightly more stratified than on the 1949 cruises in May, apparently owing to the intrusion of cold, highly saline water across the shelf on the bottom. On this is superimposed freshened water from the relatively high runoff during March and April. The temperature and salinity distribution have tended to reinforce each other in the production of a rather stable density structure. The density distribution suggests a slight southerly coastal current down the center of Onslow Bay with a slight northerly countercurrent inshore. Such motions can only serve to further dilute the river effluent and weaken the coastal current. This appears to be borne out in the June, 1953, data.

June 9-10, 1953; Caryn Cruise 64 (Fig. 18)--One section across Onslow Bay and one across Raleigh Bay comprise the June 1953 data. Since May, 1953, the water had increased in temperature at all depths over the inner half of the Onslow Bay shelf. The decreased runoff since April together with rather complete mixing and dispersion of freshened water with shelf water are reflected in the increased salinity of the surface waters. The intrusion of water with a salinity greater than $36\ ^{0}/_{00}$ had receded. The temperature and salinity distribution have combined to continue to produce a rather stable density distribution. The coastal current had degenerated to a very weak affair.

From these examples of the hydrographic structure of the shelf waters in Onslow Bay it is apparent that the overall picture is much simpler than that over the shelf north of Cape Hatteras. The shallow depths, the short distance from the coast to the continental edge, and the swift Florida Current flowing along that edge permit the transfer of runoff through the area at a rather rapid rate. Winds and the rotary tidal currents in the shallow waters increase mixing and resist the development of strong density gradients.

Fresh-water content--Estimates of the fresh-water content on the continental shelf on the several occasions have been made by planimetering the areas between the isohalines on the salinity sections, Table 2. Sea water salinity was assumed to be $36.0\ ^{0}/_{00}$.

Table 2--*Fresh-water content of Carolina shelf waters*

Date	Cruise	Pct of total volume[a]			Fresh-water volume × 10^{10}m^3			
		Raleigh	Onslow	Long	Raleigh	Onslow	Long	Total
Jan. 1950	*Albatross III*-30	0.14	0.10	0.20	0.030	0.047	0.034	0.111
Feb. 1950	*Albatross III*-32	0.02	0.10	0.11	0.004	0.051	0.019	0.074
Mar. 1948	*Reliance*-4	0.63	1.63	0.80	0.133	0.800	0.137	1.070
Apr. 1948	*Reliance*-6	0.19	1.09	0.97	0.041	0.534	0.166	0.740
May 1949	*Caryn*-7	- -	0.44	0.78	- -	0.214	0.134	- -
May 1949	*Albatross III*-18,19	0.00	0.75	1.28	0.000	0.368	0.220	0.588
May 1953	*Caryn*-64	- -	1.43	- -	- -	0.704	- -	- -
June 1953	*Caryn*-64	0.21	1.53	- -	0.044	0.751	- -	- -

[a] Total volume to 100-fm line: Raleigh Bay 21.15 × 10^{10}m^3; Onslow Bay 49.11 × 10^{10}m^3; northern part of Long Bay 17.16 × 10^{10}m^3; grand total 87.42 × 10^{10}m^3.

It is clear from Table 2 and is quantitatively indicated that the volume of fresh water contained in the waters over the North Carolina shelf varies from time to time by more than one order of magnitude. It is also clear that the fluctuations in fresh-water volume are associated with the gross sustained fluctuations in runoff. We have not been able to derive a satisfactory relationship between the fresh-water volume and the runoff for a short period.

We conclude that the removal of water from the Carolina shelf is not steady, but is perhaps modified by the wind systems and modulations in the flow of the adjacent Florida Current [VON ARX, and Others, 1954]. A southwest wind will deflect the freshened water offshore into the frictional drag of the Florida Current where it will be quickly removed. The Florida Current may encroach, either along the bottom where it displaces water at that depth and forces freshened water off at the surface, as was observed to occur on another part of Caryn Cruise 64, or it may move in bodily at all depths, sweeping coastal water out of the area, presumably to the north where it becomes part of the Gulf Stream or slope water.

Surface observations at Diamond Shoals Lightship over a period of nearly six years reveal large, and frequently sudden, fluctuations in the water temperature owing to the passage to an fro of the interface between the colder waters from north of Cape Hatteras and the waters of Raleigh Bay influenced by the Florida Current. Meander-like encroachments of the Florida Current onto the shelf and recessions from it appear to be one of the logical explanations for these fluctuations. Correlations with wind direction and force are patently unsatisfactory. Yet northeast storms are effective in driving Middle Atlantic coastal water southerly across Diamond Shoals.

Light winds which produce no great frictional effect and onshore winds will permit fresh water to accumulate on the shelf. These influences make it possible for fresh water to diminish with increasing runoff or to accumulate on the shelf with a falling runoff. But from the overall point of view high sustained runoff produces a large relative volume of fresh water on the shelf (that is, March, 1948) and a low sustained runoff yields a relatively low fresh-water volume.

Summary--The hydrography of the continental shelf off North Carolina, south of Cape Hatteras, is controlled by an environment which produces moderate horizontal gradients and weak to moderate vertical gradients in temperature and salinity. In winter water temperatures may range from 10°C at the coast to 22°C only 60 mi to the southeast. Salinity is as low as 18 $^{0}/_{00}$ in the sounds, bays, and rivers, and approximately 32 $^{0}/_{00}$ at the inlets, yet a salinity of 36 $^{0}/_{00}$ may occasionally be found within ten miles of the coast and never farther than 50 mi away. Gradient conditions are greatest in Raleigh Bay, less strong in Onslow Bay, and least in Long Bay, owing chiefly to the geography; that is, widening of the continental shelf toward the southwest. The seasonal progression of temperature and salinity distribution may frequently be modified by intrusions of the Florida Current over the continental shelf. This intrusion may be especially broad in Raleigh Bay.

Nontidal currents over the shelf may be so slow that they are barely detectable, yet just over the edge of the continental shelf the Florida Current ceaselessly flows at speeds greater than 150 cm/sec. Six reasons why a dynamic coastal current is a transient affair in this region are given. The nontidal currents over the inner parts of the shelf appear to result from the balance of forces at work, tending northerly in general but turning southerly when the pressure gradient is modified sufficiently by the runoff to counteract the thermal effect, or the frictional drag of the southerly winds or the Florida Current.

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ON THE MEASUREMENT OF BOTTOM STRESS IN LAKES

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Abstract--The rate of decrease of amplitude of the persistent small-scale wind-induced seiche in a lake is primarily a function of bottom stress. This idea is developed and a number of measurements presented.

Method--It has been shown that the rate of increase of the seiche amplitude in Lake Mendota, Wisconsin, is a function of the increase in wind speed over the lake, consequently of the surface stress [STEARNS, 1952]. Tending to decrease the momentum supplied by the surface stress is the bottom stress. After the initiating gust stops, it is proposed that the energy imparted to the water, resulting in the formation of the seiche, is dissipated primarily by the action of the bottom stress.

Assuming that the lake is suitably represented by a rectangular basin, the mean potential energy per unit area of the seiche may be written [LAMB, 1945]

$$E_p = \rho g \eta_0^2/8 \quad \ldots\ldots\ldots\ldots (1)$$

where g = gravity, ρ = density of water, and η_0 seiche amplitude at one end of the basin. Since the mean kinetic energy in a standing wave is equal to the mean potential energy of the same wave (averaged with respect to time), we see that the root-mean-square velocity is

$$V = (1/2)\,\eta_0\,(g/D)^{1/2} \quad \ldots\ldots\ldots\ldots (2)$$

where D is the average depth of the lake. The area of the bottom of Lake Mendota is very nearly that of the lake surface, whence the average loss of momentum through unit area is

$$\tau_b\,(\mathrm{eff}) = -(1/2)A\,d(mV)/dt = -(m/2A)\,dV/dt \approx -(m/2A)\,\Delta V/\Delta t \quad \ldots\ldots\ldots\ldots (3)$$

where m = mass of the lake and A = area of the lake. Thus

$$\tau_b\,(\mathrm{eff}) \approx -(1/4)\rho\,(g\,D)^{1/2}\,\Delta\eta_0/\Delta t \quad \ldots\ldots\ldots\ldots (4)$$

Data--The basic data for this study were obtained by mounting Leupold-Stevens water level recorders on suitable stilling wells at various places around Lakes Mendota and Monona. Twenty clear-cut cases of seiche decrease following impulsive wind stress generation were found (Table 1). The observed seiche period, 25.3 min, agrees with that calculated by the DEFANT [1929] numerical integration method. The values obtained are for the average bottom condition, in this case smooth organic 'sludge'. Few comparative data are available. LESSER [1951] and REVELLE and FLEMING [1937] have computed bottom stress values from the current velocity profile near the bottom. Their figures are presented in Table 2 for comparison. Since estimated currents are indicated in Table 2, the mean drag coefficient for the single July and three August, 1951, cases computed for Lake Mendota gave a value of 0.033 for a mud bottom while the value (computed) for REVELLE and FLEMING [1937] data was 0.045 for a gravel-sand bottom.

We may estimate the dynamic viscosity if we assume the velocity one meter off the bottom to be approximately the mean as derived from the data of Table 1 and Eq. (2). This yields a value of 35 to 140 g/cm/sec which is in rough accord with the values given by SVERDRUP [1946, p. 482].

Finally, SVERDRUP [1927] has pointed out that in general if the amount of energy that is dissipated by friction in a standing wave is proportional to the total energy of the wave, an exponential decrease of amplitude should result. The observed cases plotted in Figure 1 show that this exponential decrease actually occurs in Lake Mendota.

Table 1--Data for calculation of τ_b (eff) from seiche records

No.	Date	Maximum displacement η_0	Change in amplitude $\Delta \eta_0$	Time interval Δt	τ_b (eff)
		cm	cm	sec	g/cm sec^2
1	6-28-51	2.5	1.22	16200	0.03
2	6-30-51	0.6	0.46	3600	0.04
3	7- 3-51	0.9	0.85	9000	0.03
4	7-8- 51	4.0	3.80	9900	0.12
5	7-16-51	0.6	0.46	1800	0.08
6	7-17-51	0.6	0.46	3600	0.05
7	7-19-51	0.4	0.38	4500	0.03
8	7-21-51	1.2	1.07	5400	0.06
9	7-26-51	0.4	0.40	1800	0.06
10	7-27-51	0.5	0.46	3600	0.03
11	8- 3-51	0.5	0.46	2500	0.05
12	8- 8-51	2.0	1.91	9000	0.06
13	8-14-51	1.5	1.50	7300	0.06
14	8-15-51	1.8	1.07	3850	0.07
15	8-20-51	0.7	0.60	2500	0.06
16	8-28-51	0.9	0.84	3600	0.07
17[a]	4- 6-52	1.3	1.07	7500	0.04
18[a]	10-30-51	1.3	1.07	4500	0.06
19[a]	10-30-51	1.3	1.15	2400	0.10
20	8-27-51	0.5	0.38	1500	0.07

[a] Cover data for Lake Monona; all other items are for Lake Mendota; seiche period (observed), 25.3 minutes; average depth of Lake Mendota, 14 meters.

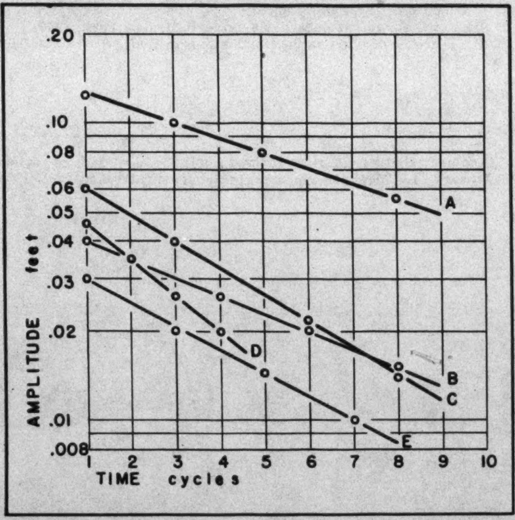

Fig. 1--Exponential decay of seiche amplitude, Lake Mendota, Wisconsin; dates; A - July 8, 1951, B - June 28, 1951, C - August 8, 1951, D - August 14, 1951, and E - July 3, 1951

Table 2--A comparison of bottom stress measurements on Lake Mendota from seiche records and bottom stress measurements made with current meters

No.	Date	Wisconsin data; bottom stress from seiche records	Estimated bottom current velocity	Bottom stress after Lesser San Diego Bay	Bottom type	Bottom stress after Revelle and Fleming San Diego Bay[a]	Bottom type
		gm/cm sec^2	cm/sec	gm/cm sec^2		gm/cm sec^2	
1	7- 8-51	0.12	10.0	0.49	Gr-snd	0.46	Smooth[b]
2	8-14-51	0.06	5.0	0.21	Mud	. . .	
3	8-15-51	0.07	3.0	0.32	Mud	. . .	
4	8-28-51	0.07	3.0	0.32	Mud	. . .	

[a] Revelle and Fleming's data stated that they had a smooth bottom with a current velocity of 15 cm/sec at a point 21 cm from the bottom.

[b] Bottom type refers to results of Lesser and Revelle and Fleming. Seiche data gives τ_b (eff) for average bottom.

Note: Items 1 and 2 for Lesser's data were treated as smooth turbulence by him, while items 3 and 4 were treated as rough turbulence.

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THERMALLY ACTUATED MOISTURE MIGRATION IN GRANULAR MEDIA

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Abstract--The movement of moisture in granular media with varying temperature gradients was studied by means of radioactive tracers in a laboratory. The mode of moisture movement is controlled by a critical moisture content found theoretically and experimentally to be about four per cent.

Summary--The mode of moisture movement for both the hot and cold zones of the tube containing simulated soil is controlled by a critical moisture content found experimentally to exist between 2.5 and 4.5 pct moisture content (12.5 to 22.5 pct saturation) and found theoretically to be about four per cent. This four per cent value is based on a calculation considering the thermodynamics of the liquid and vapor and the geometry of spherical particles. The physical significance of the critical moisture content appears to be that amount of moisture that causes adjacent rings of liquid at the grain contacts to merge.

If the cold sink (that is, the cold end) is in unfrozen condition at a moisture content above the critical, there is no evidence of any moisture migration. With freezing conditions at this wetness, there is a pronounced movement in the liquid state only, with the moisture being supplied from the area adjacent to the frozen zone.

Furthermore, above the critical moisture content there is evidence of circulation of vapor away from, and liquid toward, the hot end.

Below the critical the hot end does not experience the above vapor-liquid convection cycle nor does the cold end experience any liquid migration with or without freezing conditions. However, there exists a movement of moisture in the vapor state away from the hot end and accumulating at the cold end. This phenomenon is independent of freezing.

Fig. 1--Photograph of the apparatus

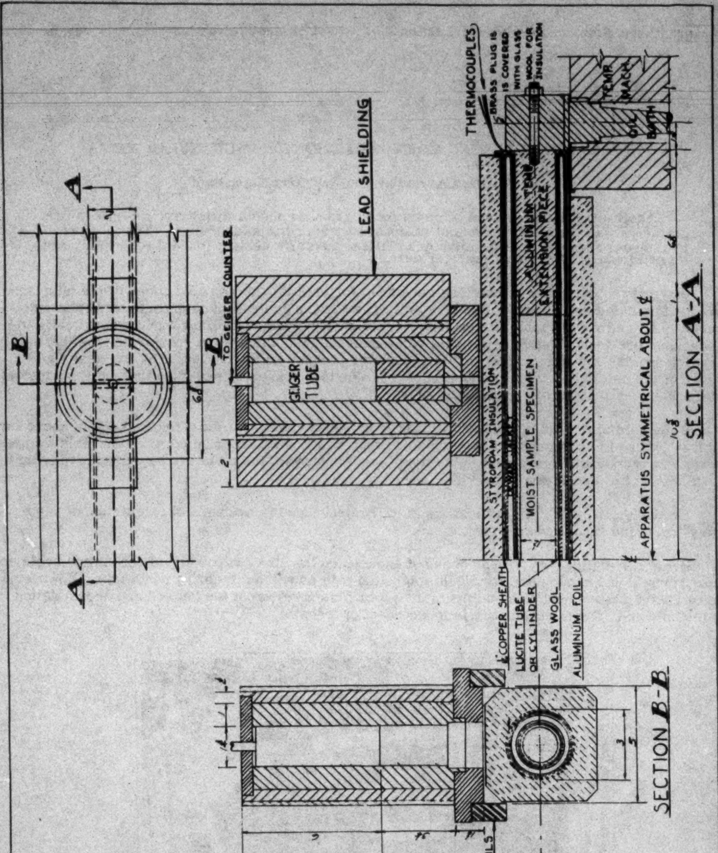
A
B
LEAD SHIELDING
TO GEIGER COUNTER
GEIGER TUBE
THERMOCOUPLES
BRASS PLUG IS IS COVERED WITH GLASS WOOL FOR INSULATION
TEMP. MACH.
OIL BATH
ALUMINUM TEMP. EXTENSION PIECE
STYROFOAM INSULATION
MOIST SAMPLE SPECIMEN
APPARATUS SYMMETRICAL ABOUT ℄
SECTION A-A
℄ COPPER SHEATH
LUCITE TUBE OR CYLINDER
GLASS WOOL
ALUMINUM FOIL
RAILS
SECTION B-B

Fig. 2--Details of the apparatus

Introduction--When a temperature gradient is imposed on a granular medium, such as a soil containing moisture, the moisture moves in the direction of heat flow. Originally it was thought that the movement would be by vapor diffusion only. It was shown by others [BOUYOUGOS, 1915; SMITH, 1943; HADLEY, 1949] that vapor diffusion was insignificant when large voids were present and that capillary spaces were apparently necessary to this phenomena.

The phenomenon is important whenever a heat source or sink is buried in the ground. This situation exists in buried electrical transmission cables, mine shafts, heat pump ground coils, etc. In the case of a heat sink there has been some discrepancy between theory and practice indicating more heat was absorbed by the ground coil than theory would predict [see HADLEY, 1949, Fig. 3]. This fact, plus a general deficiency in knowledge in this area, instigated the present investigation.

Apparatus--This study was carried out in the specially built apparatus shown in Figure 1. Heating and refrigeration equipment were contained in each of the two black boxes on either end of the table so that a temperature gradient can be produced and maintained along the tube connecting them. This connecting 1-1/2 inch diameter methyl methacrylate (Lucite or Plexiglass) tube is thermally insulated by a close fitting Dewar Flask surrounded by a copper jacket and Polystyrene Foam Insulation (Fig. 2). The copper jacket is to form a rough thermal gradient cutting down still further the radial heat losses. Inside the tube is a granular medium resembling soil. It is composed of small glass beads, spherical in shape and screened for size. For purpose of determining the effect of particle size two diameters of beads were used; the smaller, approximately 0.001 inch in diameter, gave a medium resembling fine beach sand. Screened beads of the same material, with careful control of the packing and the bulk density [EISENSTADT, 1953] makes the soil reproducible and possibly subject to mathematical analysis. The behavior of natural soils may deviate from the results obtained since all tests were conducted on this idealized soil medium.

The liquid in the soil was water containing a radioactive salt (cobaltous nitrate or chloride) as a tracer (in the concentration of about 0.1 gm of cobalt compound per liter). The presence of this salt can be detected at all times, without disassembling the apparatus, by a Geiger tube and counter shown at the top of Figure 1 and in the closeup in Figure 3. The Geiger tube can be moved along the soil and positioned at any point parallel to the axis of the tube.

If the moisture moves in the liquid state the counts per minute registered by the external Geiger tube (Fig. 4) will be directly proportional to the moisture content within the tube. (See Appendix 1 for qualification of this statement). If the moisture moves in the vapor phase there will be no change in radioactivity with time but there will be a change in moisture content observed by weighing and drying samples at the end of a run (see Fig. 5).

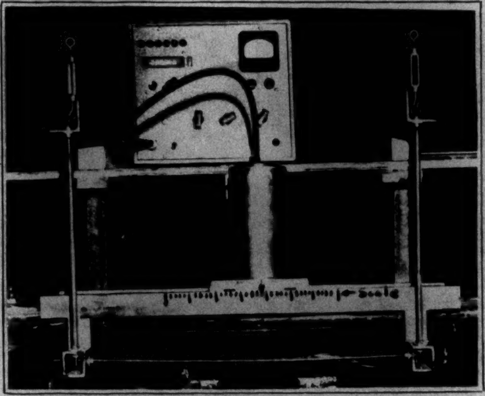

Fig. 3--Close up of the Geiger tube installation

The radioactive salt also gives good evidence as to the uniformity of the distribution of moisture at the beginning of the test due to loading. Special care and attention were necessary to obtain uniform loading and special techniques were developed [HADLEY, 1949]. Basically this involved the change from loading the specimen tube in the vertical position from a mixture prepared in one batch, to loading in the horizontal position of compacted sections obtained from ten mixing flasks.

The radioactive tracer revealed the non-uniform distribution of moisture which results from mixing and loading by the techniques used by investigations heretofore. Up to the present the dis-

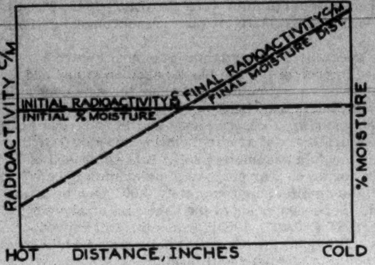

Fig. 4--Ideal case of pure capillarity

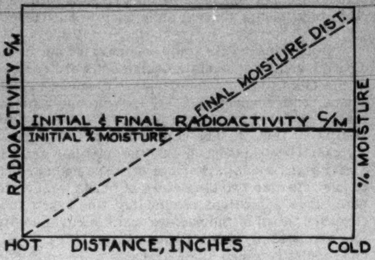

Fig. 5--Ideal case of pure evaporation

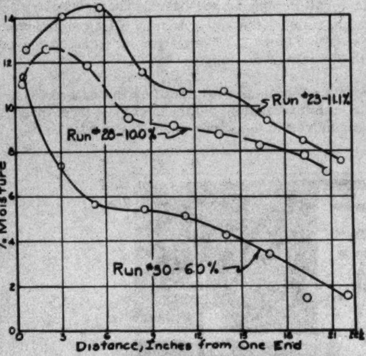

Fig. 6--Relationship of moisture content to distance for several runs illustrating effects of poor loading technique (each run is supposed to be uniform at the percentage shown

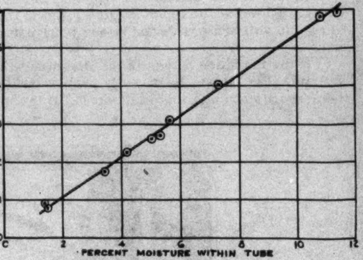

Fig. 7--Relationship of radioactivity c/m to percent moisture content within tube; no temperature gradient applied; data taken from Run 30

tribution of moisture at the beginning of a run could not be determined because moisture was measured by disassembly, drying, and weighing.

Figure 6 shows the type of poor moisture distribution obtained with conventional loading. The runs in Figure 6 were loaded vertically and the wide variation in radioactivity revealed that in loading in a vertical position the moisture had seeped down the tube by gravity. Figure 7 is a plot of radioactivity as indicated by the counts per minute indicated by the Geiger counter for an improperly loaded tube and it shows an excellent correspondence between radioactivity and moisture content within an experimental error of plus or minus five per cent. This correspondence holds true even after a temperature gradient is applied, provided that moisture movement is in the liquid state.

Figures 8 - 12 show several curves. The abscissa in all cases records inches from the hot end, the cold end being at 21-1/4 inches or (for Fig. 7) 22-1/2 inches. The temperature variation along the specimen is obtained from thermocouples inserted in the tube. Temperature equilibrium should exist on the specimen on all runs exceeding 60 hours. This was based on the consideration of an ideal thermally insulated bar with the ends subjected to a sudden temperature change [EISENSTADT, 1953]. Initial and final radioactivities are plotted. Final moisture content is also plotted. It is obtained by weighing and drying small samples abstracted immediately at the conclusion of the run through specially provided ports in the specimen tube, and by drying and weighing sections of the remaining soil specimen. The points labelled 'final moisture content' are average points derived by this double check on final moisture content.

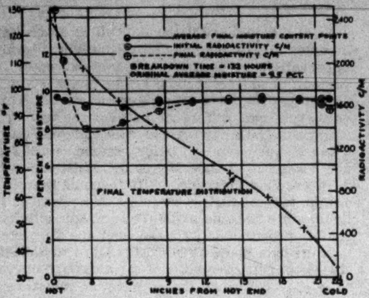

Fig. 8--Relationship of temperature, moisture, and radioactivity to distance; Run 31; 0.01-inch beads; above freezing

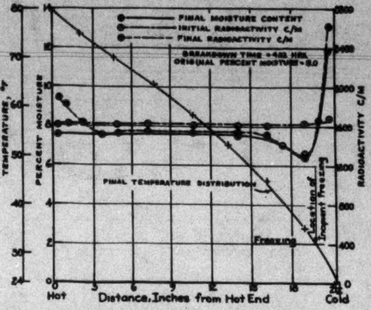

Fig. 9--Relationship of temperature, moisture, and radioactivity to distance; Run 34; 0.01 inch beads; below freezing

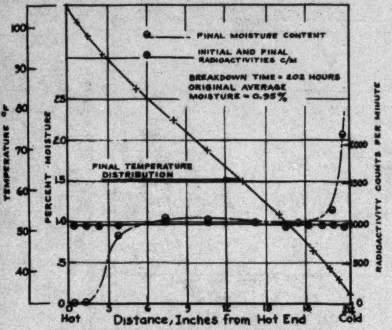

Fig. 10--Relationship of temperature, moisture, and radioactivity to distance; Run 37; 0.01 inch beads; above freezing

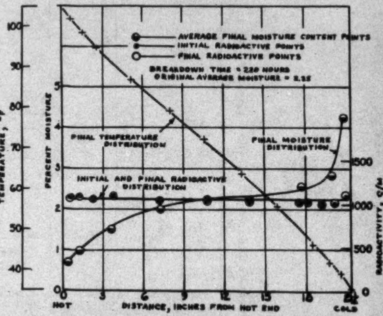

Fig. 11--Relationship of temperature, moisture, and radioactivity to distance; Run 38; 0.001-inch beads; above freezing

All percentages are weight of water per dry weight of the beads; 100 pct saturation corresponds roughly to 22 pct moisture for a porosity of 0.37 which was the average density used.

Discussion of results--A radioactive rise at the hot end can be observed in all runs above four per cent initial moisture content but not below this value. (There is no rise in moisture content associated with this radioactive rise.) Therefore, this is apparently an isolated phenomenon involving vapor circulation. This problem is being studied in detail at Columbia University at the present time and it is hoped that it can be made the subject of additional papers in the near future. This radioactive rise takes place without any corresponding change in water content. We believe this phenomenon to be due to water evaporating at the hot surface leaving the radioactive salt behind and moving as vapor in the direction of the cold end. It apparently condenses in the region adjacent to the hot end and moves as liquid back to the hot end to compensate for the evaporation, carrying salt from this region to the hot face. This provides an adequate explanation of both the rise in radioactivity at the hot end and the depletion in the adjacent region, without apparent change in the moisture content. However, we have no proof that this hypothesis is correct although we are working in the laboratory to attempt to confirm it.

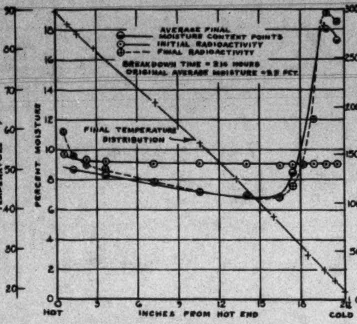

Fig. 12--Relationship of temperature, moisture, and radioactivity to distance; Run 39; 0.001-inch beads; freezing run after 163 hr

At the cold end there are two or more distinct methods of moisture movement (neither of which apparently have been previously observed or reported). The first method can be observed by comparing Figure 8 with Figure 9 and 12. The only significant difference between the former set and the latter is that the cold ends of Figure 9 and 11 were run well below freezing while Figure 8 was run at about the same total temperature difference but unfrozen. With freezing there is a definite indication of moisture movement in the liquid state because moisture and radioactivity remain proportional. These runs are all wetter than the data of BOUYOUCOS [1915] and SMITH [1943] but representative of the moisture of most soils in practice. In these cases the moisture is apparently obtained initially from the region adjacent to the freezing, which as time progresses in slowly replenished from the rest of the sample. Figure 13 illustrates this motion which is typical of other runs.

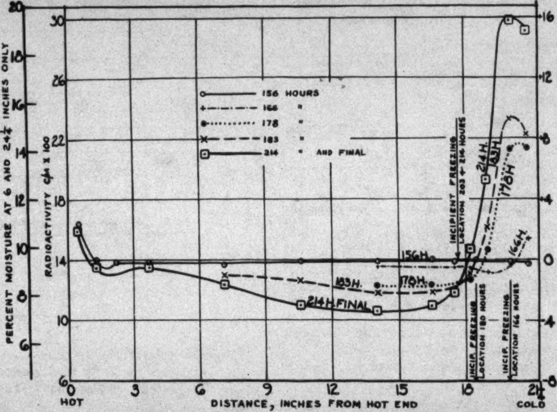

Fig. 13--Relationship of differences in radioactivity C/M from zero time, radioactivity, and moisture to distance; data from Run 39; cold end at 34° F for 163 hours (see temperature curves, Fig. 14)

At first it was considered that the freezing decreased the size of the capillary spaces in the soil which increased the forces associated with them and hence caused the moisture migration. However, Figures 9 and 12 were run above freezing with no moisture movement noticed before freezing. To decrease the capillary spaces, 0.001-inch beads were used (Fig. 12) compared with 0.01-inch beads in the other run. In Figure 14 (the temperature distribution curve for Fig. 12 and 13) it will be seen that the temperature was lowered after 163 hours. With the drop below freezing, immediately migration began (see Fig. 13). Notice that stable temperature distributions were obtained prior to the 163rd hour and again before the run was concluded. As this run behaved substantially like the runs with particle ten times the diameter and the corresponding capillary spaces, it was concluded that it was not the effect of increase in capillary forces due to the creation of smaller size voids that was causing the moisture to move. A theory using the motivating force as one involving concentration differences fits the experimental evidence more adequately. Water on freezing converts all liquid into the solid phase. In effect this deprives the cold zone of its liquid and produces a large concentration difference of liquid between the zone adjacent and the frozen section. This effect can be likened to that of thrusting a large number of fine ice capillary tubes into a reservoir of water. This will

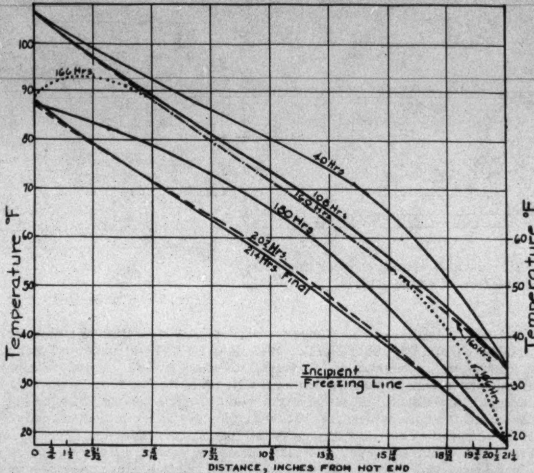

Fig. 14--Relationship of temperature distribution at various times to distance from the hot end; Run 39; after 163 hours the temperature at both ends was dropped 15° F

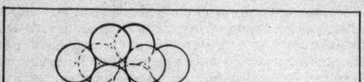

Fig. 15--Section of the cellular structure

induce water to flow into these capillaries, due to surface tension, and as this water freezes into solid, additional liquid will flow. Consider a drop of water placed on a horizontal surface having a temperature gradient. Assume a fairly well defined boundary where freezing starts. Within a short time all the water on the cooler side of the freezing line will be ice. Due to the fact that a new clean surface of ice is presented to the remainder of the drop of water, surface tension will draw some of it across the incipient freezing line and thus effect a moisture migration. The depleted area can receive moisture from the remainder of the specimen by a similar process since there is a region of relatively lower moisture content from which moisture is in the process of being removed. This accounts for the dip seen in Figure 13 which can also be observed in the data for other runs under similar conditions. There is some experimental evidence to indicate that when there is a fluctuation of the cold end above and below freezing, moisture movement is more pronounced [EISENSTADT, 1953; HADLEY and EISENSTADT, 1953] and this migration accounts for the very high moisture contents observed in the soils surrounding heat pump ground coils that have operated below freezing.

A second phenomenon is observed when Figures 10 and 11 are compared with the remaining runs. These two runs differ from the other runs by the fact that they both have relatively low moisture contents. In these runs there is moisture migration without freezing but apparently all movement

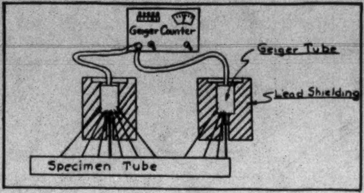

Fig. 16--Schematic diagram showing geometry correction and 'end effects'

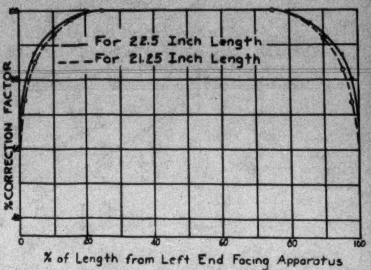

Fig. 17--Correction curve for geometry

is in the vapor phase as there is no change in radioactivity with time and moisture movement. Earlier work [BOUYOUCOS, 1955; SMITH, 1943; HADLEY, 1949] indicated that a structure embodying capillaries was necessary to moisture movement at this level of wetness. It was suggested at that time that the major movement was in the liquid state due to the necessity of having capillary spaces to produce significant moisture movement. The necessity for having capillaries may still be present but the data of Figures 10 and 11 indicate vapor movement only. It is possible that vapor diffusion across the capillary spaces is the mechanism involved. Further work is contemplated in this area. Here again particle size makes very little difference. (Compare Figure 9, using 0.01 inch beads with Figure 10 using 0.001-inch beads.) Since the predominant moisture movement in the liquid phase is at high moisture contents, while at low moisture, the moisture moves in the vapor phase, there is an implied critical condition at an intermediate moisture content.

Probably the most important conclusion reached in this investigation is that there is a critical moisture content, hitherto unknown, that separates these two distinct methods of moisture movement. A possible explanation of the critical condition is as follows: In considering an arrangement of spherical particles in a unit cellular configuration as shown in Figure 15, one notes that there are relatively narrow entrance and exit passages with a comparatively large unoccupied pore volume in between. At the critical moisture content range two effects occur: (1) Adjacent rings of liquid between the grain contacts merge providing continuous threads of liquid throughout the medium making possible capillary movements (motion in the liquid state). (2) When adjacent rings of liquid merge (or are slightly above this moisture content) they either so restrict or seal the narrow entrance and exit passages to the unit granular arrangements as to offer an extremely high resistance to the flow of vapor to the point where this flow is restricted to a negligible quantity.

If a calculation is undertaken, based on the geometry and thermodynamics of spherical soil particles, to determine the percentage of moisture that defines the transition of moisture from isolated rings to interconnected capillary threads [SMITH, 1936], a figure of approximately four per cent moisture is obtained [EISENSTADT, 1953].

Conclusion--There appears to be a critical moisture content at about four per cent moisture of the total dry weight which determines the mode of moisture movement for both the hot end and the cold end.

At the hot end there is evidence of circulation of vapor away from the heat source and liquid toward it for soils above the critical moisture content. Soils below the critical did not exhibit this movement. At the cold end there is moisture movement in the liquid state at moisture contents above the critical when freezing occurs. Although this work sheds light on the discrepancy between theory and practice with regard to heat-transfer calculations concerning moist porous media, additional work still must be undertaken before calculation of the discrepancy can be made. No moisture movement in the liquid state was observed without freezing conditions at the cold end. Below the critical moisture content there is moisture migration above and below freezing. The fact that this movement in this range is in the vapor phase is at variance with, but reconcilable to, the work of previous investigators. There is no question that moisture plays an exceedingly important role in the dissipation or absorption of heat, wherever a heat source or sink occurs in the ground.

APPENDIX 1

The term 'radioactivity' as used on the vertical axes of all curves and in the text refers to the counts per minute registered by the Geiger counter (for each section of the soil sample) modified as indicated below by the correction for geometry and the background count.

The geometry correction is necessary because the Geiger tube, even though shielded with four inches of lead, receives radiations from other areas of the specimen tube (Fig. 16). Therefore, at the ends of the soil specimen, there is an apparent decrease in radioactivity due to the fact that the tube receives radiations from one side only. The geometry of this pattern is seen in Figure 17, which was taken from a tube containing water and radioactive salt only, and hence of uniform activity. This curve was used to adjust all measurements of radioactivity to compensate for this variation due to system geometry [SMITH, 1936].

Subtraction of the background count (roughly 50 c/m) is necessary since the background is not part of the radiation originating from the moisture (that is, a Geiger counter always indicates some activity due to cosmic disturbances, etc., even though there is no radioactive substance present).

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FLOW OF GEL AND OIL IN OPEN AND TIGHT FORMATION FRACTURES

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Abstract--Open fractures refer to fractures sufficiently separated to have a very large effective permeability and which permit fluid flow at appreciable velocities; consequently fluid pressures at the source can be maintained for such fractures only at high injection velocities. Tight or closed fractures refer to fractures which have a low to moderate effective permeability and which will not permit flow at appreciable velocities; consequently hydraulic pressures in such fractures become nearly equal to the injection pressure. The difference between the open and tight fractures is a matter of degree.

Flow characteristics and relative pressure drops of different oils and gels, as would be encountered in open formation fractures, are analyzed by means of flow observed in three different small diameter tubes. Penetrabilities of a light oil and a gel, as would be injected into tight fractures and unfractured formations, are investigated with porous ceramic bricks. The flow mechanisms of the oils and gels are found to be markedly different at appreciable flow velocities, and resultant pressure losses are higher for oil than gel in open fractures. This is because oil flows largely as a 'Newtonian' fluid, while gel flows as a thixotropic medium. By contrast, penetrability in tight fractures and unfractured rocks is much greater for a light oil than gel under hydrostatic conditions. Some relative advantages of oil and gel in formation treatments are discussed.

Introduction--In 1952, The Western Company found in a number of well treatments that both gel-sand and oil-sand injections into the Spraberry formation of west Texas appeared to result in about equal increases in oil production. The gel-sand treatment involves injecting a mixture of gel (consisting of an aluminum soap and kerosene) and sand into a formation by hydraulic pressure, and the oil-sand treatment a mixture of crude oil and sand. At that time it was somewhat difficult to explain why such different fluids could increase production by about the same amount. To investigate this problem, a number of brief laboratory tests were made at Battelle Memorial Institute to determine, first, the flow mechanism and relative pressure drops of the two fluids encountered in open fractures, and, secondly, their relative penetrability in tight fractures and in unfractured rocks.

Method of investigation

Open fractures--Open fracture conditions in this investigation were simulated with three different small-diameter tubes in which pressure drops and flow rates were observed for five different fluids. Results from these tubes were projected to those in open fractures of equivalent hydraulic radii. The fluids investigated were water, SAE 30 motor oil, Spraberry crude oil, and two different viscosity gels, one in the ratio of 187.5 lb of aluminum soap and the other of 375 lb to 1000 gallons of kerosene (that is, 85 and 170 grams of soap, respectively, per gallon of kerosene).

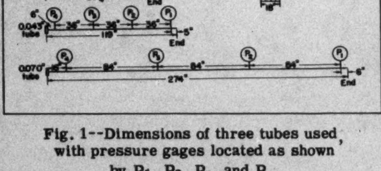

Fig. 1--Dimensions of three tubes used, with pressure gages located as shown by P_1, P_2, P_3, and P_4

Figure 1 shows the dimensions of the three tubes and the location of pressure gauges P_1, P_2, P_3, and P_4 used for pressure measurements. Velocity of efflux was calculated from the time required to fill a given volume. Fluid was forced through the tubes from a cylindrical pressure chamber 18 inches high and four inches in diameter, with an included ram. Pressures were obtained with a 150-ton capacity Watson-Stillman press whose maximum ram velocity is about 1.5 in/sec. The velocity of efflux and pressure at the four gages were recorded for each flow test.

Volume flow rates in the tubes were varied, increasing in magnitude up to 30 and 40 cc/sec. Injection pressures ranged to 10,000 lb/in^2 in many of the tests. Where the equipment could not produce such high pressures, the maximum available were used.

Preliminary tests with the two gels indicated that their viscosities did not change sufficiently within an hour after mixing to affect the test results; consequently it was not necessary to maintain absolutely uniform viscosities of the gels.

Water afforded a standard of comparison for results obtained with the other fluids. SAE 30 motor oil was used because its viscosity is known as a function of temperature [ROUSE, 1946, p. 362, graph], which permitted calculations of Reynolds numbers for different temperatures. Spraberry oil was used because it is one of the oils used in field treatments. Similarly, a treatment gel (85 grams of aluminum soap per gallon of kerosene) was used because it is a mixture commonly injected in treatments. A more viscous gel (170 grams of aluminum soap per gallon) was used to provide flow comparisons of different viscosity gels. The viscosity of the lighter gel, when fresh, is about 6000 to 8000 centipoises. That of the heavier gel is about 20,000 centipoises. (Measurements were made on Hoeppler viscosimeter at 75° F.)

Closed fractures and unfractured formations--Penetrabilities in closed fractures and unfractured media were investigated qualitatively by injecting SAE 10 motor oil and normal treatment gel into the interface between two tightly compressed 2.5 × 3 × 4.5 inch Norton 1099 refractory ceramic bricks. Fluid was injected through a hole drilled in the center of the top brick, so that the fluid was squeezed into the interface between the bricks and through the pore spaces of both bricks (see Fig. 2). Fluid pressures were applied by the same cylinder, ram, and Watson-Stillman press that were used in the investigations with tubing. Penetrability was determined only in terms of pressures required to force the fluids through the interface and the pore spaces of these caramic bricks of about 20 per cent pore space. Fluid pressures applied were up to 2500 lb/in^2.

Results

Open fractures--Average pressure drops over the first, middle, and open-end portions of the tubes (see Fig. 1) were converted into pressure drops per inch length of tubing over the respective portions of each tube. These values were plotted as functions of velocity of efflux on log-log paper and are shown in Figures 3-7 for the five fluids tested. The slopes of the curves on these figures indicate a relationship between pressure drop and flow rate according to

$$\Delta P/L \sim Q^n$$

where $\Delta P/L$ is the pressure drop per unit length, and Q is the velocity of efflux, and n is a constant.

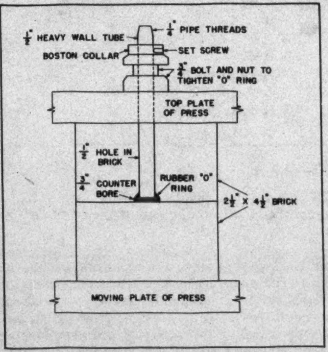
$\frac{1}{2}$" HEAVY WALL TUBE
$\frac{1}{4}$" PIPE THREADS
BOSTON COLLAR
SET SCREW
$\frac{3}{4}$" BOLT AND NUT TO TIGHTEN "O" RING
TOP PLATE OF PRESS
$\frac{1}{2}$" HOLE IN BRICK
$\frac{3}{4}$" COUNTER BORE
RUBBER "O" RING
$2\frac{1}{2}$" X $4\frac{1}{2}$" BRICK
MOVING PLATE OF PRESS

Fig. 2--Diagram of ceramic-brick testing apparatus

Within the range of tests, pressure drops per unit length were found to be constant over the length of tubing for all fluids except the SAE 30 motor oil. At the higher velocities, it was found that wall friction heated this motor oil so much in travel that its viscosity decreased appreciably. Consequently, plots on Figures 3-7 involve a constant pressure drop per unit length over the entire tubes except for the motor oil (Fig. 4), where the average pressure drops per unit length are shown over each of the three portions of the tubes.

In Figure 3 it is seen that for water in the three tubes, n is 1.0 for low velocities and about 1.8 for the higher velocities. These slopes correspond respectively to laminar and turbulent flow. The laminar and turbulent natures of these flows are verified by Moody diagrams on Figure 8, in which friction factor is plotted as a function of Reynolds number on log-log paper. The friction factor is obtained from the Darcy-Wiesbach equa-

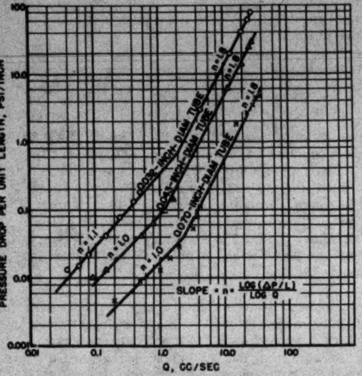

Fig. 3--Observed pressure drop of water as function of flow rate in the three different tubes

tion for energy loss due to steady fluid flow in a pipe

$$\Delta P/L = f\,\gamma V^2/2gD$$

where f is the friction factor (dimensionless)

γ is the fluid weight per unit volume
V is the average fluid velocity
g is the acceleration of gravity
D is the tube diameter

Reynolds number, also dimensionless, is defined as

$$N_r = VD/\nu$$

where ν is the kinematic viscosity.

The laminar motion is represented by the straight line portion of the Moody diagram (Fig. 8) where Reynolds number is less than 2000. The equation of this line is

$$f = 64/N_r$$

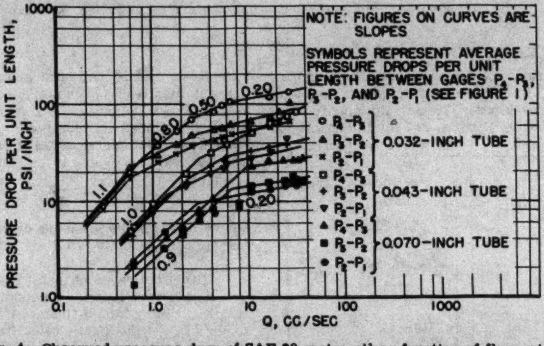

Fig. 4--Observed pressure drop of SAE 30 motor oil as function of flow rate in the three different tubes (temperature of oil, thus viscosity, varied as flow velocity in these tests)

which is obtained by equating the Darcy-Wiesbach and the Hagen-Poiseuille equations for laminar flow. Turbulent motion is represented by that portion of the diagram in which this line is no longer straight; that is, at Reynolds numbers greater than about 2000. Small temperature increases of the water in the tubes, especially in the smallest tube, were observed at the greater flow rates, but these temperature rises were not sufficient to affect viscosities of the water or pressure drops in the tubes significantly. The effect of such temperature increases would be to raise the portions of the curves in Figure 8 slightly upward for values of higher Reynolds numbers. The plotted curves are for a temperature of 70° F.

In Figure 4 the slopes of the SAE 30 motor oil in each tube are seen to be about 1.0 at the low velocities, but decrease rather than increase at the higher velocities. At low velocities, the flow thus appears to be laminar; but since resistance to flow at the higher velocities is less than for laminar motion, the motion at these velocities is not turbulent. It is also seen on Figure 4 that at low velocities the average pressure drops over the three portions of each tube are about the

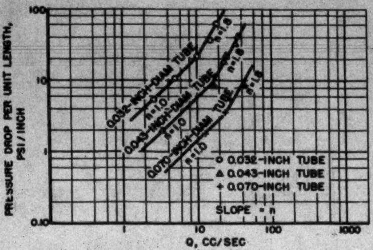

Fig. 5--Observed pressure drop of Spraberry crude oil as function of flow rate in the three different tubes

same but that at the higher velocities the pressure drops are greatest over the first portion of each tube and least over the end portion. This is a direct consequence of increasing temperature and resultant decrease in viscosity as the oil travels down each tube at the higher velocities. To further analyze the flow mechanism of this oil, the data were plotted on Moody diagrams, illustrated in Figures 9, 10, and 11.

Average temperatures of the extruded SAE 30 oil in the 0.032-inch tube were found to range from 70° F at low injection velocities to 140° F at the higher velocities. Since it was difficult to estimate exact oil viscosities in each test, Reynolds numbers were calculated for each velocity of efflux in the 0.032-inch tube, first assuming the oil temperature to be 70° F and then assuming it to be 140° F.

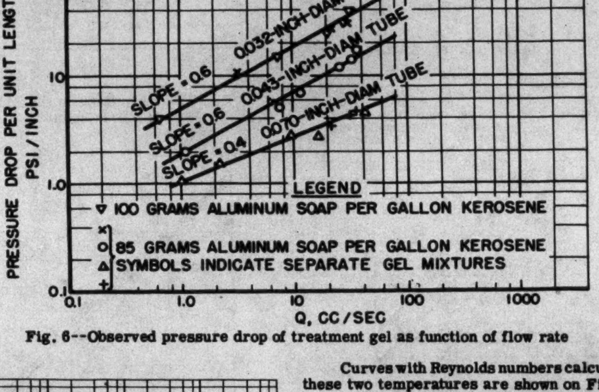

Fig. 6--Observed pressure drop of treatment gel as function of flow rate

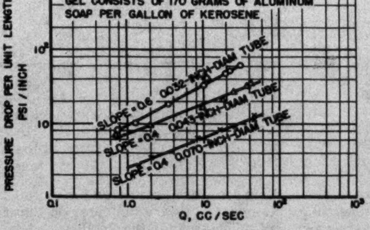

Fig. 7--Observed pressure drop of Heavy gel as function of flow rate

Curves with Reynolds numbers calculated for these two temperatures are shown on Figure 9. Since the temperature of the oil was observed to increase with velocity of flow, neither of these constant temperature curves actually applies to the flow of this oil. The true flow curve on this figure would be near the 70° F curve at the low velocities, that is, at the larger values of friction factor and smaller values of Reynolds number, and would be near the 140° F curve at the higher velocities, that is, at the lower values of friction factor and larger Reynolds numbers. A line connecting these portions of the 70° F and 140° F curves is seen to be straight and nearly parallel to a line representing laminar flow ($f = 64/N_r$). Within the range of tests, the Moody diagram for the SAE 30 oil in the 0.032-inch tube thus appears to be a straight line nearly parallel to the laminar flow line. Data for the 0.043 and 0.070-inch tubes are represented in a similar way on Figures 10 and 11, respectively.

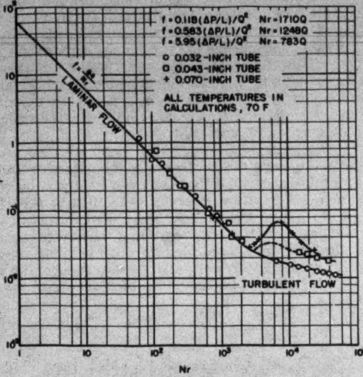

Fig. 8--Moody diagram for water in three different tubes

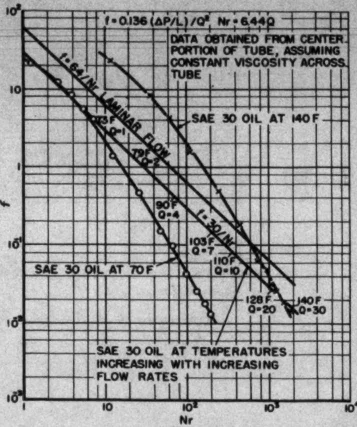

Fig. 9--Moody diagram for SAE 30 oil in 0.032-inch tube

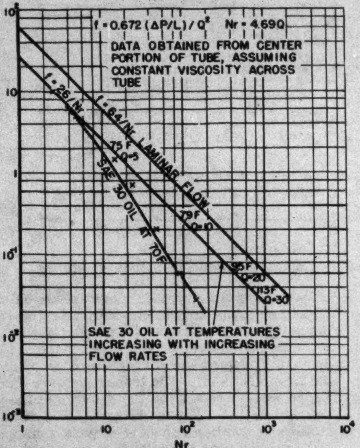

Fig. 10--Moody diagram for SAE 30 oil in 0.043-inch tube

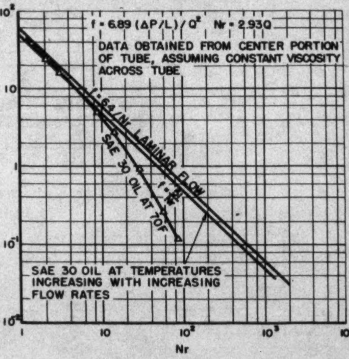

Fig. 11--Moody diagram for SAE 30 oil in 0.070-inch tube

Average temperatures that would produce these straight curves were calculated for the oil in the 0.032- and 0.043-inch tubes. Values of these calculated temperatures are indicated on Figures 9 and 10 for respective flow rates, Q. Temperatures were not calculated for the 0.070-inch tube, but they would vary similarly with velocity.

The straight line curves for oil in Figures 9, 10, and 11 assume a constant viscosity over any one cross section in each tube. This assumption is not strictly correct. Since the friction loss is largest near the walls of the tubes, the highest temperatures and lowest viscosities are to be expected near the tube walls; the lowest temperatures would be near the centers of the tubes. The offsets in the straight line curves for the oil shown in Figures 9, 10, and 11 from that for laminar flow are, therefore, probably not real, but rather indicate the difference between oil temperatures assumed in the calculations and the effective temperatures. If these data had been plotted with correct effective viscosities, in other words, the resultant curves should lie on the laminar flow curve. This is further suggested by the slopes of about 1.0 at the low velocities of the oil in Figure 4. It thus appears that within the range of tests the SAE 30 oil flows with a laminar motion that is complicated by a viscosity variation across the tube.

Figure 5 illustrates the type of flow of Spraberry crude oil over the test range. The oil is seen to flow more like water than the SAE 30 motor oil. The curves have a slope of 1.0 at low velocities, indicating a laminar flow, and a slope approaching 1.8 at the higher velocities, indicating a turbulent flow. Because Spraberry oil has a low viscosity, five to ten centipoises, only slight oil temperature increases were observed at the higher velocities and only small viscosity variations appear to occur across the tubes. Pressure drops are greater with this oil than with water, as is expected since the oil has a higher viscosity. The relative pressure drops of this oil in comparison to that of the other fluids are illustrated in Figure 12. Since variations of viscosity with temperature were not known for this oil, Moody diagrams were not constructed. The flow mechanism of this oil is quite clear from Figure 5, however, so that Moody diagrams would not add significantly to the flow interpretation.

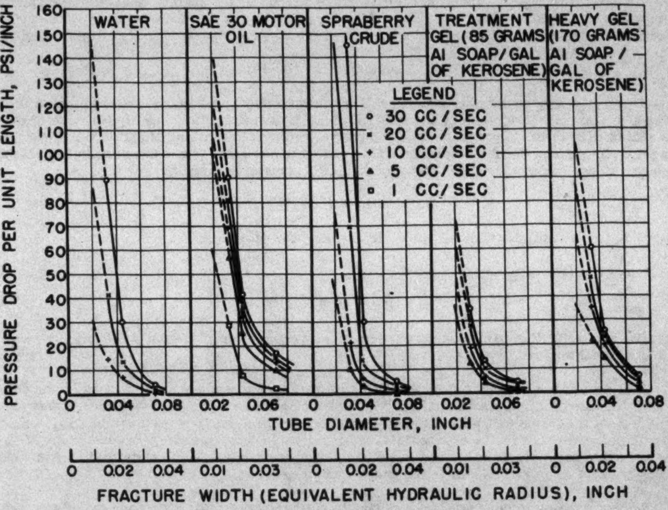

Fig. 12--Pressure drop as function of tube diameter

Figures 6 and 7 illustrate the type of flow of the two gels. Approximately constant slopes were obtained for each tube over the range of velocities used. Observe that these slopes have about the same values, not only for the three different diameter tubes, being somewhat larger for the smaller diameter tube, but are approximately the same for the two different viscosity gels. Temperatures of the gels were observed to increase only to a small extent with increasing velocities, and not enough to affect the flow mechanism.

The slopes of the curves for the gels are less than 1.0, even for low velocities, indicating that pressure drops are less than would be encountered with laminar motion. Since the gels are thixotropic, not Newtonian as were the water and the two oils, the flow should involve a marked viscosity reduction or high velocity gradient near the surface of the tubes. The viscosity of the major portion of the gel was still relatively high as it was extruded from the tubes, and it thus moved essentially as a slug in the interior portions of the tubes. This mechanism is further evidenced by the lack of temperature increase of the gels as they traveled along the tubes, even at the higher velocities. By contrast, the much lower viscosity Newtonian SAE 30 oil involved a very marked temperature increases because of surface friction where presumably no surface slip is involved. If the considerably higher viscosity gel had not slipped long the tubing walls, the temperatures produced by surface friction at the greater velocities would have been very high, indeed.

Closed fractures and unfractured formations-- The penetrability tests with the tightly clamped ceramic bricks indicated that SAE 10 motor oil penetrates the bricks to a much greater extent than does normal treatment gel (85 grams of soap per gallon of kerosene). As the fluid injection pressure in the bricks was increased to about 500 lb/in^2, the oil oozed out from the pore spaces of both the upper and lower bricks at the higher clamping loads. At these loads, more oil was extruded from the pore spaces within the bricks than from the interface between the bricks. The gel, on the other hand, was not extruded either from the pore spaces or from the interface, even at pressures up to 2500 lb/in^2.

These tests indicate, as would be anticipated, that under static pressures light oils penetrate porous materials, such as tight fractures in rocks and unfractured formations, much more readily than does treatment gel. Since the oil penetrates porous media farther than gel under static pressures, the oil contacts a larger surface of rock. Because the oil contacts more rock area, it can exert a given force per unit area on a tight fracture surface at lower applied fluid pressures.

Application of results

To a rough approximation, pressure drops in the tubes can be converted to comparable drops in open rectangular fractures by the concept of the hydraulic radius. By equivalence of the hydraulic radius (HR) in the tube diameter and fracture width, the equations of fluid flow in circular conduits can be applied to such fractures. This radius is the ratio of conduit area to wetted perimeter. Its equivalence in circular tubes and rectangular fractures is given by

$$HR = \pi D^2/4\pi D = WT/2(W + T)$$

Where W is the width of fracture, and T is the height of fracture.

In narrow fracture, where $T \gg W$,

$$HR = W/2 = D/4$$

The hydraulic radius of a narrow fracture thus equals that of a tube if the fracture width is half the tube diameter.

This equality of pressure drop in tubes and fractures of comparable radii has been demonstrated for slipless fluids with constant viscosity, even when $T = 100\ W$ or more; however its applicability for fluids that slip at the surface, such as gels, has not been established. Since considerably greater surface is exposed in fractures than in tubes, actual pressure drops of gels in fractures are probably greater than those calculated from tubes of the same radii. For gels, the radius concept is more reliable in the wider fractures.

Pressure drops in open fractures of equivalent hydraulic radii have been calculated for water, the two oils, and the two gels for various flow velocities. Figure 12 illustrates these relationships, showing pressure drops as functions of tube diameter and equivalent fracture widths at different velocities. These curves indicate that at low velocities, except in the smallest fractures, pressure drops do not vary appreciably among the different fluids. At higher velocities, especially in the smaller fractures, appreciable differences in pressure drop are indicated for the fluids. In Table 1, pressure drops of the fluids in open fractures of 0.01-inch width are approximated for different velocities. The linear velocities in this table were calculated from volume flow rates.

Although the pressure drops for the gels indicated in Table 1 are probably low, the pressure drops at the higher velocities are probably still considerably below comparable ones for water and

Table 1--Estimated pressure drops at different flow velocities for five fluids in open fractures of 0.01-inch width

Flow velocity	Water	SAE 30 oil	Spraberry oil	Treatment gel	Heavy gel
ft/sec	lb/in^2 in	lb/in^2 in	lb/in^2 in	lb/in^2 in	lb/in^2 in
150	150	140	300 ±	52	103
100	88	120	155	63	83
50	30	105	71	48	65
10	4	55	15	6	10

oil. At these velocities, pressure drops appear to be greatest for the low viscosity Spraberry oil and least for gel. Even at low velocities, gel appears to offer less resistance to flow than does either of the oils.

Estimates of injection pressures available at the bottom of a well can be made for oil by calculating pressure losses in the well tubing corresponding to given injection pressures and velocities at the well surface. Knowledge of injection pressures at the bottom of a well help delineate possible mechanisms in the ground by which treatments increase production in a formation. This problem will be treated further for the Spraberry formation in another publication. If Spraberry oil is injected into a 7000-foot column of seamless two-inch diameter tubing at a rate of five barrels per minute, the Reynolds number of the oil is calculated to be about 28,000. The flow in the tubing would thus be turbulent. A friction pressure loss in 7000 feet of two-inch diameter seamless tubing with this Reynolds number is, according to the Darcy-Wiesbach equation[2] [STREETER, 1951], about 2000 to 2500 lb/in^2. If the surface injection pressure is 2000 lb/in^2 and the head pressure of this column of oil is about 3000 lb/in^2 (allowing for sand content), the pressure the oil exerts at the bottom of the well is then 2500 to 3000 lb/in^2. Since pressure losses for gel are estimated to be less than for Spraberry oil in the well tubing at this flow velocity, the injection pressures available at the bottom of the well should be greater with gel than oil when the same surface pressures are applied. Thus, for a 2000 lb/in^2 surface pressure and a five-barrel per minute flow rate, the pressure exerted by gel at the bottom of a 7000-foot well should be in excess of 3000 lb/in^2. Exact pressure calculations for gel would be difficult to make, however. It thus appears that treatments with oil and gel at comparable surface pressures and velocities should result in quite different injection pressures at the bottom of the hole. This difference in pressures should, of course, influence strongly the effect of each fluid on the formation.

Conclusions

Investigations of fluid pressure drops in the three different diameter tubes have indicated that:

(1) Within the range of tests, the flow mechanisms of the five fluids fall into three types. Water and the Spraberry oil flow with a laminar motion at low velocities and a turbulent motion at the higher velocities; SAE 30 motor oil flows with a laminar motion at low velocities and with a modified laminar motion at the higher velocities; and the two gels appear to flow as slugs in the interior of the tubes but slip at the surface.

(2) At higher velocities, the pressure required to force gel through a tube is considerably lower than that for oil. This difference is especially marked at the higher velocities in tubes of less than 0.03 - inch diameter. At low velocities, the difference in pressure required to force the two types of fluid through the largest (0.070-inch) tube is small, although that required to force gel through the smaller tubes at low velocities is already less than that for crude oil or motor oil.

In so far as flow conditions in fractures are comparable to those in tubes of equivalent hydraulic radii, it appears that:

(1) In open fractures of width greater than 0.1 inch, oil and gel may have comparable pressure drops at even higher velocities.

(2) In open fractures of width less than 0.01 inch, the pressure required to inject treatment gel at low velocities appears to be less than that for Spraberry oil. The injection pressure required to force gel at higher velocities appears to be much less than for oil.

(3) At higher velocities, gel appears to penetrate very small open fractures which would not be penetrated by oil at the same rates and injection pressures. At high velocities gel may thus travel much farther in narrow fractures for given pressures. To force a given quantity of fluid at high velocities into open fractures would, on the other hand, require larger pressures for oil than for gel at the bottom of a well. One consequence of this is that at given injection velocities,

pressures of oil may be greater at the bottom of the well and considerably greater at the surface, so that oil could conceivably widen open fractures near the well bottom further than might gel.

In tight or closed fractures and in unfractured formations, where both oil and gel would build up to uniform hydrostatic pressures, the relative penetrability of oil and gel are quite different from what they are in open fractures. The oil would penetrate considerably farther under these conditions. By acting over a larger surface, the oil would be able to widen fractures or create new fractures at lower applied pressures than would gel.

It appears from this investigation that gel might be a better injection fluid to use in formations where relatively open fractures are being treated and where the object is to force large amounts of fluid out into formation fractures. Oil may be a more effective fluid when tight fractures are to be widened, unfractured rocks to be ruptured, or open fractures widened in which pressures that would be required with gel cannot be obtained with available equipment.

Acknowledgments

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EVAPORATION FROM AND STABILIZATION OF SALTON SEA WATER SURFACE

Harry F. Blaney

Abstract--Salton Sea was formed as the result of a break of the Colorado River in 1905 when practically the entire flow of the river discharged into the Salton Basin for nearly two years. At that time this body of water covered about 350,000 acres and reached a maximum elevation of 195 ft below sea level. For many years the excess of evaporation over inflow caused the elevation of the water surface to drop some 55 ft to minus 250 ft by 1923. Since 1935, the water level in Salton Sea has been rising. In recent years this has resulted in encroachment and damage on adjoining lands, causing concern to Federal, State, and local agencies and land owners. Therefore, three evaporation stations bordering the sea were established to study the problem. An analysis of pan evaporation, gage heights, and inflow measurements indicates that the annual evaporation from Salton Sea ranges from about 70 to 76 inches. The Federal Government has withdrawn from entry all public land in the area below the elevation minus 220 ft. Salton Sea, in January, 1954, had risen to an elevation of minus 235.8 ft and thus has leeway of 15.8 ft before reaching the minus 220-ft contour. A review of this study and other reports indicates that the water surface will continue to rise for a number of years but will eventually stabilize below an elevation of minus 220 ft prior to the year 1980.

Introduction--Salton Sea is located in northern Imperial County and southern Riverside County, California, and it occupies the lower portion of Salton Basin, which is an enclosed basin. A large part of this basin is below Pacific sea level, the lowest point being at a minus elevation of about 273 ft. The drainage area of this basin comprises some 7500 sq mi of which about 1000 sq mi are in Baja California, Mexico. Salton Sea receives not only the storm runoff from this basin, but also the drainage from some 550,000 acres of irrigated land in Imperial and Coachella Valleys, California, and 150,000 acres in the Mexicali Valley of Mexico. It provides the only outlet for surface runoff, drainage water, and ground-water seepage originating in these valleys (see Fig. 1).

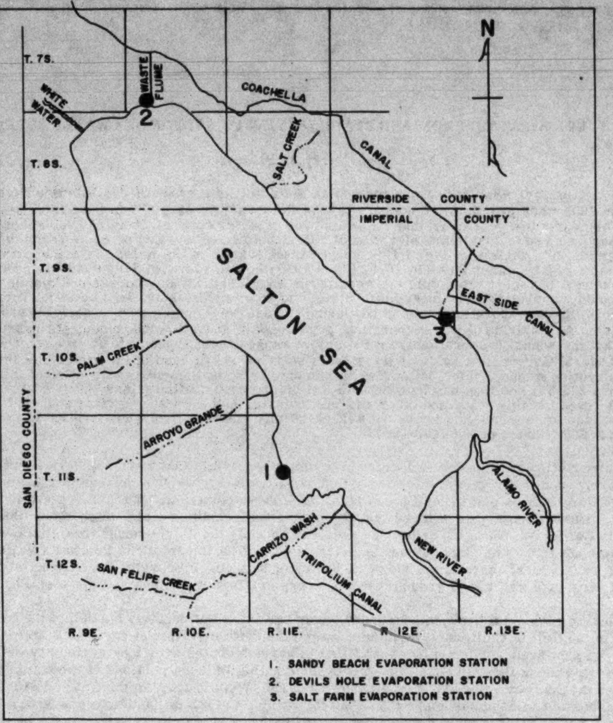
During geological time, the Colorado River has flowed alternately north into the basin and south in the Gulf of California, forming a large delta with elevation of some 40 ft above Pacific sea level. In past ages, the basin has been filled to various depths over long periods by overflow from the river. During these periods, sediments, originating in those portions of the states of Arizona, California, Colorado, Nevada, New Mexico, Utah and Wyoming within the Colorado River Basin, were deposited to depths of more than 1000 ft, forming the fertile land area now known as Imperial Valley. A shore line, now visible, indicates an ancient lake - called Lake Cahuilla by the Indians - reached an elevation of over 30 ft above sea level (this is the height at which the water would be before overflowing back into the Gulf of California).

Throughout Imperial and Coachella Valleys, there is evidence of other shorelines at lower elevations, indicating shorter periods of overflow of the river into the basin before a change in conditions in the delta forced the river to discharge back into the Gulf again.

The overflow of the Colorado River created a large lake in the Salton Basin in the 1880's and again in 1891 when over 100,000 acres of the bottom of the Salton Sink were covered with flood waters to a depth of six feet. However, dry years followed, the water in the Lake evaporated and the basin was dry when the development of Imperial Valley was commenced in 1900.

Salton Sea was formed in 1905 as the result of a break of the Colorado River which poured into the Imperial Valley for nearly two years. After that, the water level in the Sea dropped for many years, as the evaporation exceeded the inflow.

In recent years the rising water level in Salton Sea has resulted in encroachment and damage on adjoining lands, causing some concern to Federal, State, and local agencies. Therefore, in 1947, at the request of the Imperial Irrigation District of the State of California, the Division of Irrigation and Water Conservation of the Soil Conservation Service (since January 1, 1954, part of the newly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WHITE WATER
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COACHELLA CANAL
SALT CREEK
RIVERSIDE COUNTY
IMPERIAL COUNTY
SALTON SEA
EAST SIDE CANAL
PALM CREEK
ARROYO GRANDE
SAN DIEGO COUNTY
ALAMO RIVER
NEW RIVER
CARRIZO WASH
TRIFOLIUM CANAL
SAN FELIPE CREEK
R. 9E.
R. 10E.
R. 11E.
R. 12E.
R. 13E.
1
2
3
1. SANDY BEACH EVAPORATION STATION
2. DEVILS HOLE EVAPORATION STATION
3. SALT FARM EVAPORATION STATION

Fig. 1--Map of Salton sea showing evaporation stations

organized Soil and Water Conservation Research Branch of the Agricultural Research Service, U. S. Department of Agriculture) established three evaporation stations along the shores of the sea for the purpose of obtaining data to estimate future elevations of Salton Sea surface and at what level it might be stabilized. This study was under the supervision of the author until July, 1951, when the stations were taken over and continued by the Imperial Irrigation District [BRADSHAW and Others, 1951].

Formation of Salton Sea--As a result of a break of the Colorado River in the spring of 1905, practiclaly the entire flow of the river discharged into the Salton Basin for nearly two years creating Salton Sea. At the time of the closure of the break in February 1907, the Sea covered about 350,000 acres and had reached a maximum elevation of 195 ft below sea level. For the next twelve or thirteen years an excess of evaporation over inflow caused the elevation of the sea to drop rapidly. However, by 1920, irrigation development in the Imperial and Mexicali Valleys had reached a point where return flow to the Sea equalled the evaporation. For the next few years the rate of lowering slowed down with elevations leveling off until in 1925, when the low point of about 250 ft below sea level was reached. From then until 1931 there was a rise in the Sea of about seven feet due in part to a plentiful water supply for irrigation and in part to several severe local winter storms.

However, water shortages, particularly in 1931 and 1934, which caused large crop losses in Imperial Valley, resulted in a drop of several feet in the Sea to another minimum elevation of minus 248 ft in 1935 (see Fig. 2).

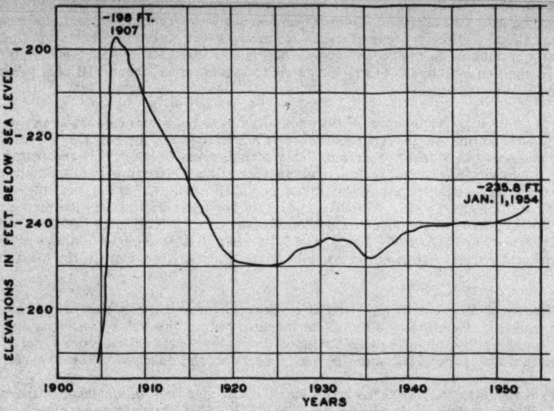

Fig. 2--Water surface fluctuations, 1904-1954, Salton Sea, California

Since the commencement of storage behind Hoover Dam in February, 1935, there has been an ample water supply available to the lower Colorado River and the Sea has been rising, although at varying rates. The elevation on January 1, 1954 was 235.8 ft below sea level and had a surface area of approximately 218,000 acres. The storage capacity of the Sea at this elevation is around 5,300,000 acre feet. For several years the level of Salton Sea has been rising more rapidly than for some time past-about 1.5 ft during 1951.

Factors involved in sea rise

There is nothing mysterious about the rapid rise of Salton Sea in the past five years. Several writers have implied that the rise was unaccountable and that little is known about the Sea. They make no mention of investigations that have been made or of monthly gage readings of the elevation since 1904. They imply that the rise threatens the existence of Imperial and Coachella Valleys. One writer attributes the rise to seepage from the Gulf of California through cracks in the delta. Another writer advances the theory that the building processes in the delta might become reversed, thus permitting the tidal bore at the mouth of the Colorado River in Mexico to erode its way through the delta and inundate these highly-developed areas in the United States. Investigations show the fallacy of these theories as they are not based on facts [DOWD, 1952; SIKES, 1937]. Recent surveys show that 50 miles from the mouth of the river the basal cone of the delta forms a barrier over 40 ft high in Mexico and from sea level on the Gulf side to sea level on the United States side, this barrier is about 65 miles wide [LAWSON, 1950]. A comparison of the early United States Navy survey in 1873 and a recent survey shows that the Gulf of California has not encroached upon this distance since that time and there has been no perceptible retrogressive changes at the mouth of the river for some eight years. Taking these factors into account, plus the fact that nature's dam has remained intact for centuries, it would seem that Imperial Valley has little to fear from the possibility of seepage from the Gulf.

There is nothing unprecedented about the rapid rise in the last several years. Whenever inflow from local rain storms and return flow from irrigation exceed evaporation, the Sea rises. Runoff from single storms has raised the elevation as much as 1.5 ft. Summer storms followed by a cool, wet fall and winter were a decided factor in the 1.5-ft rise of 1951. Other factors are the

100,000 acres increase in irrigated area, and the increase in efficienty of drainage in Imperial Valley, with consequent increase in return flow from irrigation to Salton Sea [DONNAN and Others, 1954]. In 1948, diversions from the Colorado River to Imperial and Coachella Valleys totalled 2,900,000 acre feet; in 1951 the total was over 3,500,000. Another factor was a change in the crops grown. The year 1951 saw a return of cotton to Imperial Valley for the first time in twenty years - 28,000 acres in 1951 and 88,000 in 1952. Cotton required considerable water and results in greater return-flow than some other crops. Seepage and waste water from the Coachella Branch of the All American Canal and the increased use of Colorado River water for irrigation in Coachella Valley have also contributed to the recent rise in Salton Sea level. These factors combined explain the rise of Salton Sea. No doubt as the irrigated area increases, there will be a further rise in the sea level.

Evaporation investigations--Evaporation studies have been carried on at various times by the Division of Irrigation Engineering and Water Conservation of the Soil Conservation Service (activites transferred to Western Soil and Water Management Section, Soil and Water Conservation Research Branch, Agricultural Research Service, U. S. Department of Agriculture, January 1, 1954) and its predecessors for a number of years in California, Colorado and other areas [ROBSON, 1913; YOUNG and BLANEY, 1941; YOUNG, 1947]. In Southern California studies and measurements of evaporation have been made under arid conditions such as Silver Lake [YOUNG and BLANEY, 1941], Bard [YOUNG and BLANEY, 1945], and Salton Sea [BRADSHAW and Others, 1951] as well as several semi-arid coastal areas at the request of the State Engineer of California and local agencies.

The difficulty of direct determination of evaporation from large water areas results from the general impossibility of obtaining a complete inventory of all the waters entering and leaving a reservoir. Occasionally, opportunities exist for computing evaporation from records of inflow, outflow, bank storage, precipitation on the water surface, and changes in water surface levels.

Usually, evaporation is measured from small water surfaces in standard evaporation pans such as U. S. Weather Bureau or screen pans [YOUNG, 1947]. Such measurements may be reduced to lake or reservoir equivalents through use of conversion factors or coefficients derived experimentally for the type and size of pan.

In 1909-10, after preliminary investigation, the U. S. Weather Bureau conducted some evaporation studies with pans suspended from towers off-shore above Salton Sea. However, as far as can be determined from the fragmentary published reports, the results were inconclusive.

Early estimates of evaporation from Salton Sea were based primarily on gage heights, rainfall, and estimates of inflow. Being below sea level, there is no outflow and since the bottom of the sea is composed of tight materials, seepage losses have been considered negligible.

Using such data, a few engineers have estimated evaporation for Salton Sea, the results being in general agreement. Unpublished figures prepared by the Salton Sea investigators show the average computed evaporation for the ten-year period, 1909-10 to 1918-19 to be 68.76 inches per year as shown in Table 1 [YOUNG, 1947]. In estimating these values, the inflow from Alamo and New Rivers was arbitrarily taken as 277,000 acre feet annually. The records do not show that any inflow was considered from such streams as San Felipe Creek, Whitewater River, or the numerous flood washes that enter the Sea.

Robson estimated average annual evaporation for the six-year period, April 1, 1907, to April 1, 1913, to be 65.84 inches on basis of inflow, rainfall, and gage heights [ROBSON, 1913]. Since the discharge from Alamo and New Rivers had to be estimated and there was no record of inflow from Whitewater River and San Felipe Creek, it is probable that this estimate is too low.

Probable evaporation shown in Table 2 was computed by Grunsky for the year April 1, 1907, to March 31, 1908, in the same manner, as 73.68 inches [YOUNG, 1947]. In 1927, Holbrook of the U. S. Geological Survey, in a study of probable future stages of the Salton Sea, estimated the average annual evaporation from Salton Sea based on available data as 5.8 ft [HOLBROOK, 1927].

Recent evaporation studies--The Salton Sea is located in a closed basin and provides the only outlet for surface runoff, drainage water and ground-water seepage originating in the Imperial Valley, Mexicali Valley (Mexico), Coachella Valley, and the adjoining mesa lands.

Table 1--Average computed lake evaporation from Salton Sea, California, 1909-10 to 1918-19[a]

Year	Evaporation
	inch
1909-10	72.76
1910-11	66.57
1911-12	64.22
1912-13	65.99
1913-14	68.27
1914-15	84.69
1915-16	65.23
1916-17	53.17
1917-18	69.73
1918-19	76.96
Average	68.76

[a] Source: Unpublished estimates by Salton Sea investigators, U. S. Weather Bureau.

Table 2--Computed lake evaporation from Salton Sea, California, 1907-08 [YOUNG, 1947]

Year and month		Evaporation
		inch
1907	Apr.	5.16
	May	8.52
	June	8.88
	July	8.28
	Aug.	6.36
	Sep.	11.16
	Oct.	6.84
	Nov.	6.48
	Dec.	4.20
1908	Jan.	2.16
	Feb.	2.64
	Mar.	3.00
	Total	73.68

In recent years, the rising water level in Salton Sea has resulted in encroachment on adjoining lands, causing concern to the Imperial Irrigation District and land owners.

In connection with cooperative drainage investigations, the Imperial Irrigation District requested the Division of Irrigation Engineering and Water Conservation of the Soil Conservation Service, to make a study of evaporation from Salton Sea. In July, 1947, three evaporation stations bordering Salton Sea were established in locations shown in Figure 1 by Donnan and Bradshaw under the supervision of the writer. Annual unpublished progress reports [BRADSHAW and Others, 1951] for years 1947 to 1950 present the results of evaporation studies and describe the scope of the investigations. These stations were turned over to the Imperial Irrigation District in 1951. A summary of pan evaporation for the calendar years 1948, 1949, and 1950 is shown in Table 3.

Table 3--Measured evaporation of fresh water from screen pans at three stations bordering Salton Sea, 1948, 1949 and 1950

Station	Location	Evaporation		
		1948	1949	1950
		inch	inch	inch
1	Sandy Beach	121.57	114.44	112.44
2	Devil Hole	99.26	96.13	91.25
3	Salt Farm	94.73	90.02	88.60
Mean		105.18	100.20	97.43

Pan reduction coefficients--Coefficients for converting pan evaporation to lake evaporation have been used for many years [ROHWER, 1931; YOUNG, 1947]. Evaporation records at Yuma, Bard, Silver Lake, Salton Sea, and other stations in arid locations indicate that usual coefficients for converting pan records to evaporation from lake surfaces are too high [BRADSHAW and Others, 1951; YOUNG and BLANEY, 1941]. Also this is indicated by estimates of evaporation based on gage heights and inflow into Salton Sea [BRADSHAW and Others, 1951]. The coefficient for the screen pan under desert conditions has not been definitely determined. Coefficients for Weather Bureau pan range from 0.60 for arid conditions to 0.80 for humid areas.

In May, 1938, a gage was installed under the direction of the writer in Silver Lake, ten miles north of Baker, California, along with a Class A Evaporation Station for the purpose of determining pan coefficients under desert conditions. Measured evaporation for the period May 12, 1938, to April 1, 1939, was 68.96 inches from the lake and 113.10 inches from the Weather Bureau pan, which gives a pan coefficient of 0.61. Since evaporation records of the Weather Bureau pan are more numerous and usually used in estimating evaporation from lake surfaces, screen pan records have been reduced to Weather Bureau pan evaporation by establishing a ratio between the two pans by observations at

U. S. Yuma Field Station and Sandy Beach Station at Salton Sea. The ratios of the Weather Bureau pans to the screen pans at those stations are shown in Table 4.

Table 4--Ratios of evaporation from Weather Bureau pan to screen pan

Station and location	Year	Evaporation Weather Bureau pan	Evaporation Screen pan	Evaporation WBP/SP
		inch	inch	inch
U. S. Yuma Field Station, Bard	1938	100.74	79.79	1.26
U. S. Yuma Field Station, Bard	1939	100.28	75.42	1.33
Salton Sea, Sandy Beach	1948	144.31	121.57	1.19
Mean				1.26

Estimated evaporation 1948-53--From available pan records at Salton Sea at stations shown in Figure 1 and other data, the annual evaporation from Salton Sea for the six-year period, 1948 to 1953 inclusive, is estimated to range from 70.5 to 76.4 inches as indicated in Table 5. The average annual evaporation for this six-year period is 73 inches.

Table 5--Estimated annual evaporation from Salton Sea, California, based on average pan records from three stations[a]

Year	Evaporation (fresh water) Measured screen pan[b]	Evaporation (fresh water) Weather Bureau pan[c]	Evaporation (fresh water) Lake (estimated)[d]	Evaporation Salton Sea (estimated)[e]
	inch	inch	inch	inch
1948	105.18	132.5	79.5	76.4
1949	100.20	126.3	75.8	72.9
1950	97.43	122.8	73.7	70.8
1951	101.51	127.9	76.7	73.7
1952	96.98	122.2	73.3	70.5
1953	101.82	128.3	77.0	74.0
Average	. . .	. . .	. . .	73.0

[a] Measurements in 1948, 1949, and 1950 by the Division of Irrigation Engineering and Water Conservation, Soil Conservation Service, U. S. Dept. of Agriculture in cooperation with the Imperial Irrigation District.

[b] Average of Sandy Beach, Devils Hole, and Salt Farm stations adjacent to Salton Sea.

[c] Based on average ratio of screen pan to Weather Bureau pan 1.26 established from measurements at Sandy Beach, and Bard, California.

[d] Pan reduction coefficient of 0.60 based on Silver Lake and other records [YOUNG and BLANEY, 1941].

[e] Corrected for measured salt content of Salton Sea (percentage by weight [YOUNG and BLANEY, 1945].

During the 1948-51 investigations the author considered determining evaporation from Salton Sea from measured monthly inflows from Alamo River and New River, change in sea elevations, rainfall, estimates of inflow into the sea from flood waters, through the channels of Whitewater River, San Felipe Creek and several washes, and from wasteway of the Coachella Valley branch of the All American Canal. Table 6 illustrates the results obtained for the years 1949 and 1950. The difference between the evaporation shown in Tables 5 and 6 may be attributed to the fact that the computations shown in the latter tabulations do not include corrections for ground-water seepage which is an unknown factor.

Future elevation and stabilization of Salton Sea--The question, 'At what elevation is it anticipated that the level of Salton Sea will be stabilized?' is one which deeply concerns Federal and State agencies, Imperial Irrigation District, Coachella Valley County Water District and owners of private land and resorts bordering the shores of the sea. A definite answer at this time is difficult to make since there are a number of unknown factors which will affect its future elevation. For instance, to

Table 6--Computed annual evaporation from Salton Sea based on measured gage heights, rainfall, and inflows from Alamo River and New River and estimated other unmeasured inflows

Year	Rainfall	Salton Sea		Inflow		Calculated evaporation		
		Area (average)	Average elevation (minus)	Measured Alamo and New Rivers	Other sources (estimated)	From measured data[a]	From estimated inflow[b]	Total[c]
	inch	acre	ft	ac ft	ac ft	inch	inch	inch
1949	1.92	205,500	240	1,130,416	124,400	61.4	7.3	68.7
1950	0.21	206,800	239	1,199,291	100,000	62.5	5.8	68.3

[a] Based on measured monthly inflow from Alamo and New Rivers, rainfall on Salton Sea surface and change in sea elevation.

[b] Based estimated unmeasured surface inflows.

[c] Exclusive of ground-water seepage (estimated at 70,000 acre feet per year)

date there has been virtually no attempt to provide drainage for the 150,000 acres in Baja California, Mexico, which are part of the drainage area of Salton Sea. An extensive system of drains must be constructed to permit continue profitable farming of this area. What will these drains and waste water from Mexican canals contribute to Salton Sea?

The Colorado River water contains approximately one ton of salts per acre-foot [DONNAN and Others, 1954]. The average annual depth of irrigation water applied to crops in Imperial Valley ranges from about 1.6 ft for barley to 4.7 ft for alfalfa; thus, 4.7 tons of salt per acre is added to alfalfa land annually. Most of this salt is removed by drainage systems and passed on to the Salton Sea in order to maintain a salt balance; otherwise, the lands would become so waterlogged and impregnated with salts as to become unprofitable for agriculture. Thus, the rise of water in the Sea is linked closely to the problems of water quality and drainage in Imperial, Coachella, and Mexicali valleys. As new lands are put under irrigation, the installation of tile drainage systems on farms in these valleys will increase the flow into Salton Sea. Tile drains are being installed in Imperial Valley farms at the rate of about 20,000 acres per year. While drainage systems in 1953 included more than 150,000 acres of land, there are over 1400 miles of open drains and 4,000 miles of tile lines in the valley now. Drainage systems are now being installed on some farms in Coachella Valley.

The importance of Salton Sea as a drainage basin has been realized for a great many years and studies have been made from time to time as to its behavior and what might be expected in the future. In the year 1924, the Federal Government withdrew from all forms of entry all public lands of the United States in the Salton Sea area lying below an elevation of 244 ft below sea level, and created a Public Water Reserve. At that time the elevation of the sea was approaching 250 ft below sea level, and the free-board of six feet was thought to be sufficient. But this was without a proper consideration of future conditions. The United States Geological Survey undertook an investigation of the probable future stages of Salton Sea and, in a report issue in 1927, reached the conclusion that the stabilized elevation of the sea might be between elevations 223 ft and 226 ft below sea level, but that for safety the maximum elevation should be considered as 220 feet below sea level. This is 15.8 feet higher that the present elevation. Based on these conclusions, and by Executive Order in 1928, the Federal Government withdrew from entry all public lands of the United States in the Salton Sea area lying below this elevation of 220 ft below sea level, adding the withdrawn area to the Public Water Reserve.

An analysis of the available data for the nine-year period 1945-53 shown in Table 7 indicates that the total surface inflow exceeded the evaporation by 823,400 acre feet. During this period, the level of the sea rose from minus 240.5 to minus 236.2 ft elevation, while area of the sea surface increased from 204,000 acres in 1945 to 217,000 acres in 1953. This water balance study indicates that average annual evaporation from the sea is about 72 inches.

Unpublished estimates as to when the Salton Sea will reach the minus 220-foot contour vary from the year 1968 to the year 1985. In my opinion, this elevation will not be reached prior to 1980. A review of these facts and other reports indicates that the water surface of Salton Sea will continue to rise for a number of years, the rate depending upon various factors. It remains for the future to show whether the estimated stabilized elevation of minus 220 feet may or may not be too conservative.

Table 7--Analysis of available data on Salton Sea for period 1945-53

Year	Measured inflow		Other inflow	Total inflow	Mean elevation of sea	Mean surface area	Potential evaporation (72 inches per year)	Net change in storage[b]
	Imperial Valley	Coachella Valley						
			Ac ft	Ac ft	ft	Acre	Ac ft	Ac ft
1945	1,068,100	. . .	185,000	1,253,100	-240.5	204,000	1,224,000	++29,100
1946	1,116,900	. . .	120,000	1,236,900	-239.8	207,000	1,242,000	-5,100
1947	1,068,900	. . .	119,000	1,187,900	-240.0	206,000	1,236,000	-48,100
1948	1,054,900	10,000[a]	146,000	1,210,900	-240.2	205,000	1,230,000	-19,100
1949	1,130,400	12,000	177,000	1,319,400	-239.8	207,000	1,242,000	+77,400
1950	1,143,200	52,000	118,000	1,313,200	-239.4	208,000	1,248,000	+65,200
1951	1,206,000	79,000	215,000	1,500,000	-239.0	209,000	1,254,000	+246,000
1952	1,298,000	68,000	155,000	1,521,000	-237.3	213,000	1,278,000	+243,000
1953	1,350,000[a]	75,000[a]	112,000	1,537,000	-236.2	217,000	1,302,000	+235,000
Accumulated 9-year net								+823,400

[a] Estimated.

[b] Estimated capacity January 1, 1945 = 4,400,000 acre feet
Nine-year net = +823,400 acre feet
Estimated capacity Dec. 31, 1953 = 5,223,400 acre feet
(For capacity of 5,223,400 acre feet, the elevation should be 236.2)

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A NEW METHOD FOR PREDICTING TRANSIENT STATES OF SALINITY INTRUSION INTO THE SACRAMENTO-SAN JOAQUIN DELTA

Robert E. Glover

Abstract--The mechanism by which the tidal changes propagate salinity into the Delta channels and the manner in which this propagation is opposed by the fresh water stream flows are expressed in mathematical form. Solutions of the basic differential equation are given which are suitable for computation of salinity changes and a method of computation is described. As an example of the use of these methods they are applied to the historical records to determine a depletion curve for the Delta by using the observed salinities as an indicator and finding the flows out of the Delta which were necessary to hold the salinities to the observed amounts. While the primary usefulness of this depletion curve is to form a basis for further estimates of ocean salinity encroachment, it is compared to use curves derived from independent sources.

The Delta area of California extends eastward form the head of Suisun Bay for a distance of about 25 mi. Its extent in the north and south direction is about twice as much. In primitive times it was a vast marsh with a network of channels which carried the flow of the Sacramento, San Joaquin, and the North and South Mokelumne Rivers and other smaller streams. It has been reclaimed by raising the naturally existing dikes to enclose areas which could be pumped out and farmed. The reclaimed areas are commonly called islands even though their land surface may be as much as 15 ft below sea level. Salinity encroachment has always been a matter of concern because there is a continual seepage of water into the islands. So long as this seepage water is fresh it may be useful to growing crops, but if it is saline it may be detrimental. An added interest in salinity propagation has arisen as a result of the construction of the Tracy Pumping Plant, which is supplied by water flowing southwardly through the Delta channel from the Sacramento River.

Encroachment of salinity in the Delta channels is a result of tidal ebb and flow. Tidal changes coming in from the Pacific Ocean through the Golden Gate are propagated through the San Francisco, San Pablo, and Suisun Bays to the junction of the Sacramento and San Joaquin Rivers on the western edge of the Delta. From this point they spread out to traverse the channels throughout its area. Due to the size of the channels, velocities due to river discharge are generally less than the tidal velocities, with the result that the direction of flow in them reverses during each tidal cycle. Since there are roughly two tides per day, this reversal occurs frequently. Because the flow velocities in the middle of a channel are greater than they are near the sides, the incoming tidal flow may carry a tongue of saline water form Suisun Bay into the Delta channels, where turbulence mixes it with the fresher waters in them. On the outgoing tide the process is reversed, and a tongue of fresh water enters and mixes with the more saline waters. The tidal ebb and flow thereby creates a mechanism by which salinity may be propagated into the Delta channels and, in the absence of stream flow, would ultimately establish ocean salinity in all the Delta channels. The salinity propagation by tidal action is opposed by the fresh water stream flow which tends to sweep the salinity out of the channels into the bay. In times of flood the salinity disappears from the channels, but in times of low stream flow the salinity creeps back. All of the Delta channels appear to have sufficiently turbulent flow conditions to prevent the development of a salt water wedge.

A method of computing salinity changes may be based upon the reasonable assumption that the rate of propagation of salinity by tidal action, at any point in a channel, is proportional to the salinity gradient at that point. When the tendency of the stream flow to carry the salinity toward the bay is also taken into account, this assumption leads to the differential equation.

$$\partial S/\partial t = K\,\partial^2 S/\partial X^2 + V\,\partial S/\partial X \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

where

S represents the salinity expressed in units such as parts of chloride per 100,000 parts of water

t, time in seconds
x, distance measured along the bank of a channel, positive upstream in feet
V, the velocity in the channel due to stream flow, positive if the flow is downstream, in ft/sec
K, a diffusion constant expressing the capacity of the channel for diffusing salt by tidal action in ft^2/sec

It is to be understood that the diffusion constant K for a channel is to be determined empirically from measurements of salinity changes which occur in the channel under the influence of tidal action and stream flow. A solution for the ultimate steady state is given by an expression of the type

$$S = S_o \exp(-Vx/K) \qquad (2)$$

where S_o represents a maintained value of salinity at the point where $x = 0$. A solution useful for treating transient salinity states may be obtained in the following way.

Let ξ be a length variable measured along the axis of x from the origin of x so that we can use the variable ξ to describe the location of an element of salinity at time zero and x to indicate the point at which the salinity is to be computed at some subsequent time. If the regimen of a channel has been disturbed by a change of flow, or by some other change, we know that if the new conditions persist long enough and the salinity at $x = 0$ is maintained at some value S_o, the salinity distribution will ultimately come to the steady state configuration given by Eq. (2). Suppose we designate the departure from this ultimate steady state at time zero by $F(\xi)$. Then to calculate the salinity changes between the initial configuration and the ultimate steady state, we need a solution of (1) which satisfies the conditions.

$$\left.\begin{aligned} S &= 0 \text{ when } x = 0 \text{ for } t > 0 \\ S &= F(\xi) \text{ when } t = 0 \text{ for } \xi > 0 \end{aligned}\right\} \qquad (3)$$

It is to be understood that this solution represents the departure from the ultimate steady state, and that the salinity at any time is to be computed by adding this solution to (2).

The required solution is

$$S = \frac{\exp(-V^2t/4K)}{\sqrt{\pi}} \int_0^L \frac{F(\xi)\exp[-V(x-\xi)/2K]\left\{\exp[-(x-\xi)^2/4Kt] - \exp[-(x+\xi)^2/4Kt]\right\}}{\sqrt{4Kt}}\, d\xi \qquad (4)$$

Computation methods--A graphical procedure has been devised for evaluation of (4). This process may be described as follows. Eq. (4) can be put in the form

$$S = \frac{1}{\sqrt{\pi}} \int_0^L \frac{F(\xi)[1-\exp(-x\xi/Kt)]\exp\left\{(-1/4Kt)[(x-\xi)+Vt]^2\right\}}{\sqrt{4Kt}}\, d\xi$$

Let

$$u = [(x-\xi) + Vt]/\sqrt{4Kt} \qquad du = -d\xi/\sqrt{4Kt}$$

Then if we let I represent the integral

$$I = \frac{1}{\sqrt{\pi}} \int_0^{\xi} \frac{\exp\left\{(-1/4Kt)[(x-\xi)+Vt]^2\right\}}{\sqrt{4Kt}}\, d\xi$$

The above substitution of variable will reduce the integral to the form

$$I = \frac{1}{\sqrt{\pi}} \int_0^u e^{-u^2} du \qquad = 0.5\ E(u)$$

where

$$E(u) = (2/\sqrt{\pi})\int_0^u e^{-u^2}\,du$$

The function E(u) is the probability integral for which tables are available.

With this notation we may then write

$$S = \int_{I_1}^{I_2} F(\xi)\,[1 - e^{-x\xi/Kt}]\,dI$$

or

$$S = \int_{E_1}^{E_2} 0.5\,F(\xi)\,[1 - e^{-x\xi/Kt}]\,d\xi$$

It will now be possible to arrange a graph on which

$$0.5\,F(\xi)\,[1 - e^{-x\xi/Kt}]$$

is plotted as abscissa against the variable E. Corresponding ordinates and abscissas will have the same value of ξ. Evaluation of the integral may then be accomplished by means of a planimeter. A chart of this kind is shown in Figure 1. The computations used in the preparation of this chart are shown in Table 1.

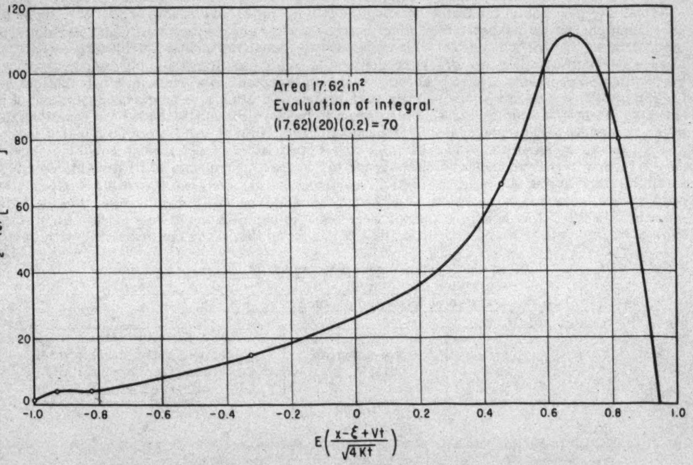

Fig. 1--Chart of computation of salinity at Bulls' Head Point, June 20, 1929

In the computations in Table 1

K = 2,900 ft^2 / sec
V/2K = 0.000019913
x/Kt = (36.239) $(10)^{-6}$
4Kt = (5011.2) $(10)^{6}$
Area 17.62
Correction: (20) (0.2) (17.62) = 70

V = 0.1155 ft/sec
x = 45,400 ft
t = 432,000 sec (5 days)
x + Vt = 45,400 + 49,896 = 95,296
$\sqrt{4Kt}$ = 70,780
Salinity on June 15 is 300

Then the total salinity at Bulls' Head Point on June 20 is 300 + 70 = 370.

Table 1--Computation of ordinates and abscissas, salinity at Bulls' Head point, June 20, 1929

ξ	$F(\xi)$	$x\xi/Kt$	$1-e^{-x\xi/Kt}$	$0.5F(\xi)[1-e^{-x\xi/Kt}]$	$(x-\xi)+Vt/4Kt$	E
ft						
0	0	0	0	0	1.346	0.9430
26,700	250	0.968	0.6202	77.5	0.969	0.8294
45,400	275	1.645	0.8070	111.0	0.705	0.6812
64,700	145	2.344	0.9041	65.5	0.432	0.4588
116,100	30	4.207	0.9852	14.8	-0.294	-0.3224
162,500	7	5.889	0.9972	3.5	-0.949	-0.8204
186,900	8	6.773	0.9988	4.0	-1.294	-0.9328
289,300	3	10.483	1	1.5	-2.741	-0.9999
435,000	0	15.763	1	0		-1.0000

Preliminary studies--Before the methods described in the previous paragraphs could be used for the actual estimation of salinity changes in the Delta, it was necessary to develop an idealization and to find values for the essential constants which would make the computations yield results in conformity with observations made during past years. The years 1924, 1929, and 1931 were particularly useful for these purposes because they were years of low runoff which produced well-developed salinity patterns in the Delta. Among the factors to be developed by trial were those of an equivalent channel cross section, channel lengths, and a corresponding diffusion constant. Since these choices are not independent, it was decided to choose a channel of arbitrary cross section, to seek corresponding distances for the stations at which salinity was to be computed, and a value for a diffusion constant. It was also found to be advantageous to work from a hypothetical location for the point $x = 0$ such that the salinity at this point will always be at the concentration of ocean salinity. An idealization of this kind may seem to be over-simplified, but if the equations described in the preceding paragraphs of this memorandum are studied it will be realized that it is equivalent to, and at the same time much simpler to use, than other choices which could be made even though these alternative choices would appear to be more appropriate at first sight. The choices finally arrived at are shown in Table 2. In making these choices, use was made of information developed several year ago by operation of an hydraulic model of the Delta, in addition to the historical situations in the Delta. Separate studies were made to evaluate the effects of surface storage and bank storage on the flows past Collinsville. It was found that these factors were negligible.

Table 2--Constants required for salinity computations: diffusion constant, $K = 2900\ ft^2/sec$; area of cross section of idealized channel, 132, 500 ft^2;

Point	Distances from origin, x	Salinity factors (assumed ratio of mean tidal cycle surface zone salinity to observed salinities[a])
	ft	
Point Davis	26,700	0.94
Bulls' Head Point	45,400	0.86
Bay Point	64,700	0.90
O and A Ferry	116,100	0.84
Collinsville	162,500	0.83
Antioch	186,900	0.82
Jersey	289,300	0.76
Rio Vista	435,000	0.74
Central Landing	485,000	

[a] Estimated from comparison of data in Tables 25 and 33, Bulletin 27, CALIFORNIA, STATE OF [1931a]

Flow depletion in the Delta--A knowledge of the amount of water lost or diverted from the Delta channels is of importance because it is one of the factors which helps to determine the amounts of water which must enter the Delta if the salinity encroachment is to be held in check. Because much of the water supply to the islands is supplied by seepage, a determination of Delta depletion is attended with unusual difficulties. Efforts at evaluation have generally taken the form of studies of the use of water by crops, of evaporation losses, and the like from which the use and losses could be estimated with the aid of crop survey and water surface area data. For salinity propagation studies, such data may not be suitable because the part used by plants may have been diverted from the channels some time earlier to be stored temporarily in the soil. We will therefore distinguish between the terms depletion and use, using the former to designate water diverted from the channels and the latter to indicate water quantities as determined by studies of the type described above. It is, of course, the depletion data which are needed for studies of salinity propagation and an independent method for determining a curve of depletions, such as is shown in Figure 2, will now be described.

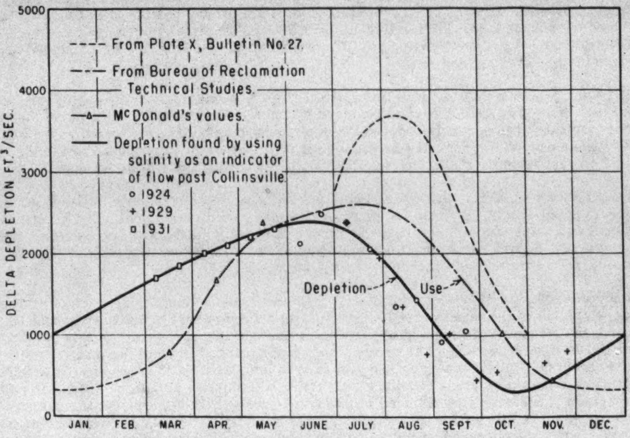

Fig. 2--Comparison of various Delta depletion curves

Having obtained, by trial, a group of constants which give a satisfactory correlation with experience, it becomes possible to derive a Delta depletion curve by using the salinity as an indicator and working back to the flows which would be required to pass out of the Delta at Collinsville to hold the salinity to the observed values. The process was carried out in the following way. In a year of record, such as 1924, for example, a beginning time was chosen at which a usable salinity pattern had developed. A trial outflow was then chosen and the changes in salinity computed for some subsequent time. The usual interval was 15 days. The computed salinities were then checked against the observed salinities, a new trial value was chosen, and the computation repeated. When a satisfactory correlation was found, the process was applied to the succeeding 15-day interval. The result of these computations was a series of computed values for the flow past Collinsville. The Delta depletion was then computed by deducting the flow past Collinsville from the inflow to the Delta. Delta inflows were obtained, when necessary, by applying a formula essentially similar to the one described on pages 424 to 427, inclusive, of Bulletin 27 (a) of the State of California. The year 1924 provided data from which outflows for the months June through September could be computed; the year 1931 provided data useful through the months of March to May. Values obtained for the year 1931 subsequent to May indicated depletions decidedly lower than were obtained from 1924 and 1929. It seems reasonable that this should be the case since 1931 was a year of heavy salinity encroachment which interfered with the normal use of water. For this reason the computations for the year 1931 were not carried past the months of early summer even though a usable salinity pattern was available. The records of the years 1924, 1929, and 1931 permitted calculation of the outflow past Collinsville for all the months except December, January, and February. The depletion curve obtained from these computations is shown on Figure 2. Use curves obtained from Bureau of Reclamation technical studies and from other sources are also shown for purposes of comparison.

The procedure used for finding the depletion curve of Figure 2 is an indirect one. This process should be effective, however, for finding a depletion schedule which will work with the computation procedure described. The whole process described herein, of which the depletion curve of Figure 2 is a part, may be considered to be a process of correlation which, used as a whole, may be useful for predicting salinity states in the Delta. While no claim is made that the depletion curve obtained in this way does accurately represent Delta performance, it is of interest that the results indicate a depletion which antedates use, as it should, and also that the maximum rates are not greatly different from those developed on other grounds by the Bureau of Reclamation technical studies.

Another comparison was made by completing the use curve obtained from the technical studies and comparing total yearly use and depletion. Data for the months of March, April, May, October, and November were supplied by Harris McDonald. Data for the months of December, January, and February were taken from Chapter II of Bulletin 27 (a). The total yearly use comes out 1,008,000 ac-ft while the total yearly depletion is 1,051,000 ac ft. These two figures should be equal. The discrepancy is about four per cent.

It seems probable that the depletion pattern changes somewhat from year to year. Changes in the types of crops grown should cause some changes in the depletion pattern. In the past, salinity encroachment has probably reduced the depletions in very dry years such as the year 1931. In years when essentially normal conditions prevail, however, it is proposed to use the curve of Figure 2 to represent the depletions for the purpose of estimating salinity changes in all cases.

It was observed earlier that operation of the Delta model with depletions based on the use data of Plate X of Bulletin 27 (a) would not produce correlation with historical salinity patterns. Although this model is no longer available, it is the opinion of those familiar with its operation that the depletion curve of Figure 2 has magnitudes and a maximum occurring at about the right time of year to correct the discrepancies which were previously found.

Study of 1949 salinities--In order to test these methods against the records of a recent year, they were applied to the data for 1949. This year had a water supply which was about 63 per cent of normal and antedates the opening of the Walnut Grove Cut. The results of this study are shown graphically on Figures 3 and 4. The computations are arranged to yield the mean tidal cycle surface zone salinity. Salinity samples are generally taken about 1-1/2 hours after high-high tide with the intention of obtaining a sample which represents the maximum salinity during the tidal cycle. A comparison of the salinities obtained in this way with the results of observations extending over a complete tidal cycle indicates, however, that maximum salinities are not always obtained by such samples. Before the observed salinities can be compared with the computed values, it is necessary to obtain from them an estimate of the mean tidal cycle surface zone salinity. To do this use was made of the data in Table 25 of Bulletin 27 (a). From a comparison of these data with those of Table 33 (a) a series of factors was derived relating the mean tidal cycle surface zone salinity to the observed salinity. These factors are listed in Table 2.

A plot of the observed values of salinity will show a considerable variation. These variations are probably due to the variation of effectiveness of tidal diffusion of salt by the spring and neap tides. The process of computation described above does not account for this variation of tidal activity and, therefore, the computed values should be compared to an average of the observed salinities after correcting to give the mean tidal cycle surface zone salinity. An example of the process for reducing the observed salinities is shown on Figure 4. The observed salinities are first plotted and then a curve averaging the observed values is drawn by eye. The factors of Table 2 are then applied to yield the mean tidal cycle surface zone salinity. In the plot of Figure 4, data for Martinez were substituted for the Bulls' Head data because data for the latter station are not given in the Report of Sacramento - San Joaquin water supervision for 1949.

Control flow--The unchanging flow past Collinsville required to hold the salinity at Antioch permanently to 100 parts of chlorine per 100,000 parts of water may be estimated from formula 2 to be about 5,900 cu ft per second. A similar value was obtained earlier from operation of the Delta Model. The discrepancy between this figure and those obtained from studies made in the Delta itself caused some concern because these values, even though obtained under difficulties, were based on observation and should not be lightly cast aside. It is believed that the present studies go a long way toward reconciling these differences because they indicate that the salinity repulsion caused by the winter and spring flood flows is effective for sufficiently long periods to reduce the control flow requirements very substantially below the above amount during the low inflow period at the end of the summer. The flow needed to control salinity would approach this figure only if sufficient reservoir capacity were available to completely contain the winter and spring flood flows.

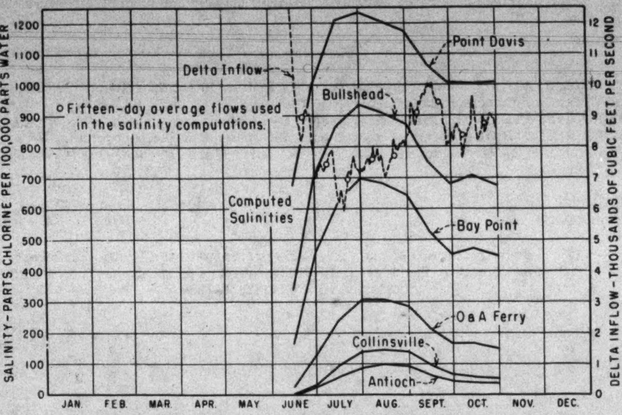

Fig. 3--Computed mean tidal cycle surface zone salinities for 1949

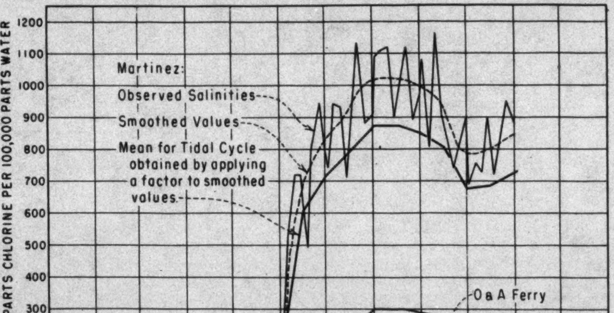

Fig. 4--Mean tidal cycle surface zone salinities as obtained from observations in 1949

Acknowledgments--The formulas presented herein have been checked by Q. L. Florey. A part of the preliminary computations, as well as the computations of depletion for the years 1929 and 1931, was made by him. L. J. Mitchell made a part of the preliminary computations for the year 1924. He also made salinity state computations for the year 1949, as well as a study to evaluate the effect of bank storage in the Delta. Some values used for plotting the use curve, as shown on Figure 2, were contributed by H. R. McDonald. Helpful suggestions have also been received from D. J. Hebert.

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GRAPHICAL ANALYSIS OF TREND PROFILE OF A SHORTENED SECTION OF RIVER

Sam Shulits

Abstract--The effect on the profile of shortening a stretch of river by one or more cutoffs is analyzed graphically. The method is based on the observation that river slope and particle characteristics of bed material are closely related. The constructed profile is that towards which it trends as a result of the rectification, but which it may never attain due to geologic and other unforeseen conditions. The time to reach this trend profile is still unpredictable. The method illustrates the consequences of the interplay of cutoffs.

Introduction--One of the purposes of river shortening or rectification, usually by means of cutoffs, is to steepen the slope to induce scour or degradation of the riverbed; that is, to deepen the channel, perhaps to contain floods. Frequently ignored is our ignorance of the depths to which the river will descend, or the profile towards which it will trend. This so-called 'trend profile' is the subject of this paper.

As any theory or explanation must be based on observations, it is most fortunate that a long-time and long-known record of the consequences of channel straightening exists for a considerable portion of the Rhine River in Germany. Since the records start in 1828, over a century of observed behavior can be studied - a geological instant perhaps, but a significant time interval to the engineer.

The Rhine River rectification--Between 1817 and 1842, eighteen cutoffs were made in the Rhine River in the reach from Sandhofen to the junction with the Lauter River. This reduced the talweg from a length of 84 miles to 53 miles, or 37 pct. The correction was continued upstream to Basle by confining the braided river to a uniform channel. This extensive corrective measure resulted in a recorded progressive lowering of the bed in the period from 1820 to 1925. In 1927 after a study of almost a century of records, WITTMAN [1927] concluded that the 250 miles of the Rhine River between Basle and Bingen had still not stabilized in 1925, even though some of the corrective works were then more than 60 years old.

A personal inspection in January, 1950, of the Rhine River from Balse to Breisach revealed that this degradation had not yet stopped and was progressing downstream. This is shown strikingly by Figure 1, 2 and 3. Figure 1 compares the 1830 and 1947 low-water profiles. The Rhine River has suffered a very considerable and continuing lowering of the bed, the admitted result of the drastic rectification between 1817 and 1842.

The Rhine degradation is shown best in Figure 2, where the 1828 low-water stage is used as a zero reference for about 80 miles of river from Basle to Strasbourg. The low-water stage had dropped about 22 ft at Rheinweiler and 4 ft at Marlen. The degradation has progressed steadily downstream. The movable Kembs dam, near Basle, arrested the recession there about 1933. There has not been the opportunity to inquire into the cause of the aggradation at Rheinau.

Any seeming stabilization after a rectification program must be regarded with a wary eye, as is demonstrated by Figure 3. At Rheinweiler, about 13 miles below Basle, degradation did not begin till after 1860, but has continued ever since. Seventy years passed before the lowering reached Breisach, about 33 miles below Balse, but a damaging degradation has persisted there since 1890.

At Mannheim retrogression started in 1842 and continued for 12 years to 1854, after which no change occurred till 1869. In the five years from 1869 to 1874 the bed dropped farther, then remained unchanged for 13 years to 1887, since when there has beeen uninterrupted degradation. Between 1825 and 1925 the low-water stage sank a total of 4.9 ft. Thus, an apparent steady-stage condition, even for 10 years, does not necessarily denote stabilization.

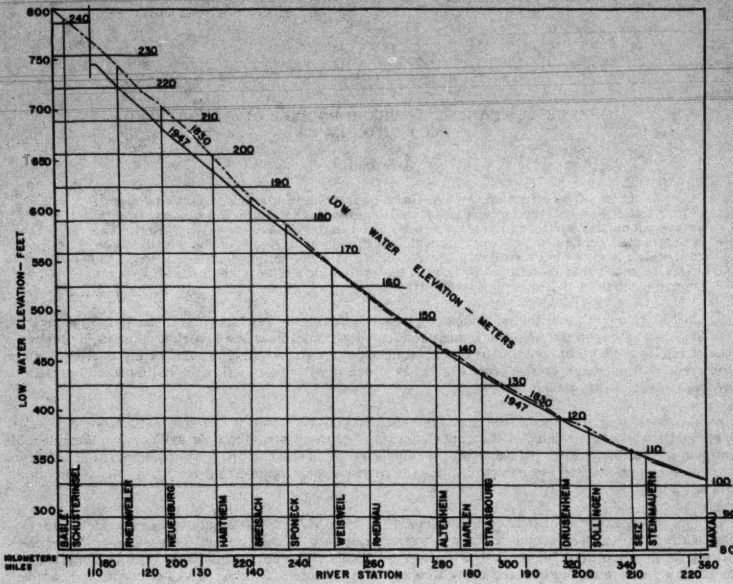

Fig. 1--Low water profile - Rhine River - 1830 and 1947 - Basle to Maxau (540 m^3/sec at Basle)

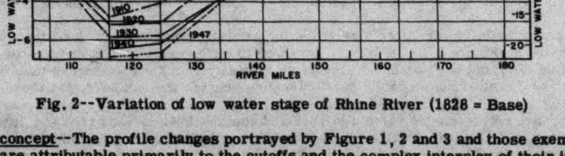

Fig. 2--Variation of low water stage of Rhine River (1828 = Base)

Basic concept--The profile changes portrayed by Figure 1, 2 and 3 and those exemplified at Mannheim are attributable primarily to the cutoffs and the complex interplay of their individual patterns of aggradation and degradation. Might one dare to offer an analysis that is at least plausible, of these observed trends in the regime of a rectified river?

As river sediments wander downstream, a systematic and progressive change occurs in the sediment properties, such as roundness, sphericity, particle size and weight, sorting coefficient,

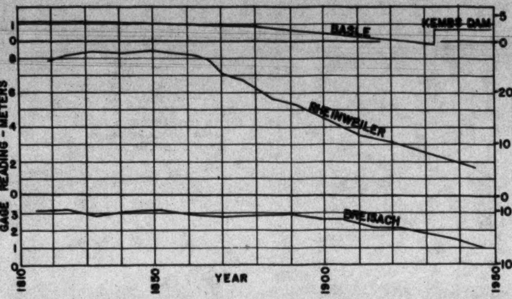

Fig. 3--Recession of low water stage of Rhine River (540 m^3/sec)

and even particle density or specific gravity. Present-day thinking is that selective transportation, or sorting, accounts for the largest part by far, of the observed changes in transit, and that only a very small share can be attributed to abrasion or particle wear [KRUMBEIN and SLOSS, 1951, p. 168]. PETTIJOHN [1949, p.433] believes 'selective sorting of materials of diverse nature is the only complete and wholly consistent explanation.'

The river slope also changes systematically and progressively downstream; there seems to be a relationship between the slope and the sediment properties. Could not one go a step further to postulate, that in a shortened reach of river, the sediments delivered to some unchangeable point in the river will be those formerly found upstream a distance equal to the shortening? This idea would tie sediment characteristics, sorting, and abrasion, to distance and as a final step, to the slope. The basic premise or deduction is then: If a river is shortened, the slope tending to be established at the first downstream control, will be that formerly existing upstream a distance equal to the shortening. This steeper slope might be designated the 'trend slope.'

This idea has been used before but was related solely to abrasion [SHULITS, 1936]. The concept has been broadened here to embrace selective sorting. It will also be shown to be illuminatingly applicable to a series of cutoffs.

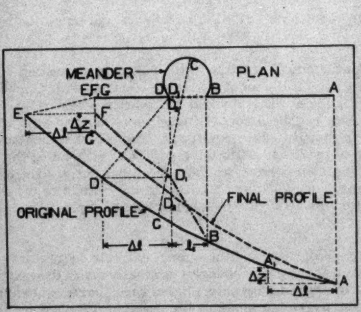

Fig. 4--Effect of cutoff on river slope

Single cutoff--Application of this reasoning to a river cutoff is illustrated in Figure 4. The original slope is AA_1BCDE, where A and E are controls at which the elevation cannot change. AA_1BD_1F (the dot-and-dash line) is the slope at the instant of cutoff. AD_2G (the dash line) is the trend slope and is obtained by moving A_1BCDE down to A. The point A_1 is upstream from A, the lower control, a distance (Δl) equal to the shortening. The profile has been shifted a distance Δl horizontally and Δz vertically. The result is aggradation downstream from the cutoff and degradation above, the generally accepted picture of the action of cutoffs.

As the method is entirely graphical, the river profile equation need not be considered. Should an equation be desirable, see MACKIN [1948, p. 463] and SHULITS [1941].

The device of sliding the original profile downstream can be employed to delineate pro-

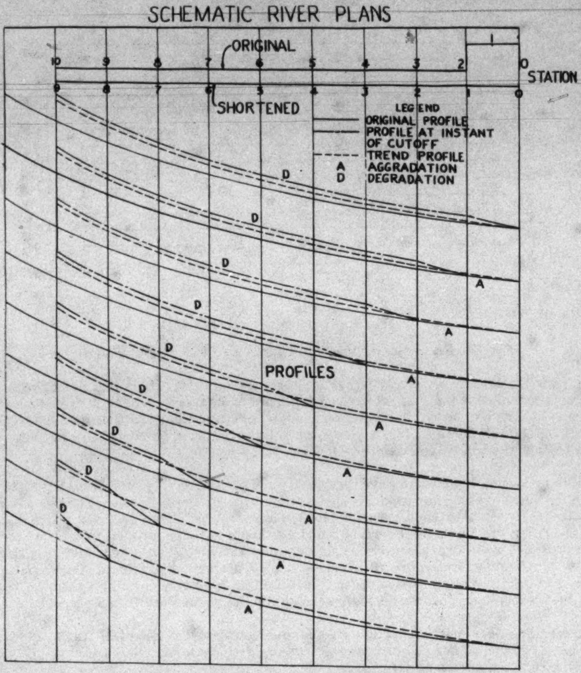

Fig. 5--Single cutoff in various positions

files which conform with the fact that the unstable conditions in the Rhine are caused by the continuing interaction of numerous cutoffs.

Position of single cutoff--The position of a single cutoff relative to the controls above and below it governs the conformation of the trend profile. The plan of a stretch of river with a bend or meander is shown schematically at the top of Figure 5. The block at 1 presents a bend, first at position 1, then in eight other positions (2-3, 3-4, etc.). The amount of shortening is the same in each case, that is, it is the same bend and cutoff in nine different positions. The effect of replacing the bend by a cutoff is illustrated by the nine sets of profiles. With the cutoff in position 1 at the downstream control, the trend is toward degradation everywhere, as the uppermost set of profiles predicts. The middle set (cutoff at 5-6) shows the consequences of a cutoff in the middle of the reach - aggradation below the cutoff and degradation above it; the preceding Figure 4 also illustrated this condition.

If the cutoff is in position 8-10, at the upper control, aggradation seems entirely to be the trend. As the position of the cutoff moves upstream, the picture changes gradually from the one extreme of degradation only, to the other extreme of aggradation only. In between there is always a combination of both, that is, aggradation below and degradation above the cutoff.

Two cutoffs--The effect of two cutoffs between the controls is represented in Figure 6. Two conditions are illustrated: Bends first at B′ and B_1 and then at B″ and B_2. The distance between B″ and B_2 is roughly 50 pct greater than that between B′ and B_1 but the bends and cutoffs B′ and

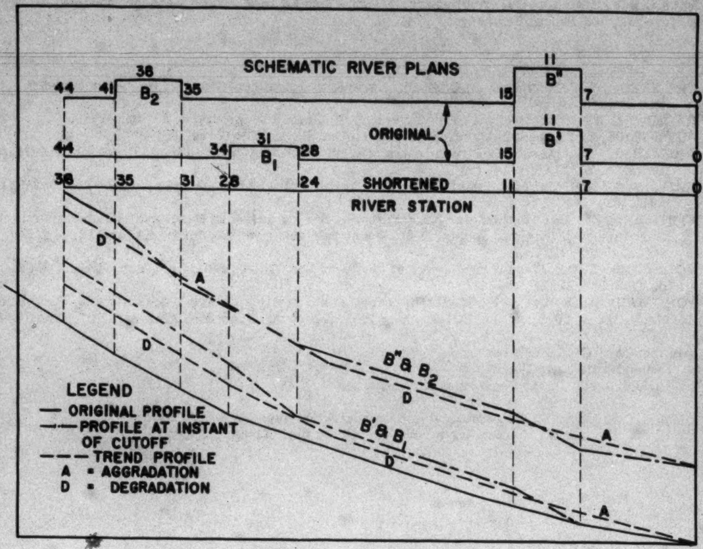

Fig. 6--Two cutoffs - various distances apart

B'' are identical. For the combination B' and B_1, aggradation is indicated below B' and degradation above B' everywhere up through the cutoff at B_1 to the upper control.

For the combination B'' and B_2 there is the typical aggradation below the downstream cutoff. Above B'' the result is, progressing upstream, first a reach of degradation, then a stretch of inappreciable or no ultimate change, followed by slight aggradation just below B_2, and finally degradation above B_2.

It is easy to imagine that there could be an unlimited assortment of bed configurations, depending on the positions of controls and cutoffs, and the number and lengths of bends and cutoffs. The suggested and so-called trend profile is that toward which the shortened reach of river might conceivably trend. The long-range unstable stages in the Rhine are quite understandable when one thinks how complicated must be the mutual influence of the different cutoffs, from the instant of cutoff to the indeterminate time of regime equilibrium. The time element is, of course, still a mystery.

Conclusion--A graphical analysis is possible of the effects of cutoffs on the river profile, based on the concepts of selective transportation and abrasion of particles. The analysis yields trend profiles which resemble the observed effects of the interplay of a series of cutoffs, for example, on the Rhine River.

The trend profile is not the ulitmate profile that will be due to the rectification. If all the natural phenomena concerned, geologic, meteorologic, hydrologic and so on, remained the same as they were at the time of straightening, the profile would trend toward that obtained by the graphical method- this is the limit of the pretensions of this proposed prediction method. The ultimate profile, geologic periods away, is beyond the scope and knowledge of this investigation. The ultimate profile, when achieved, will be a geologic-long-term and all-river adjustment to the geologic, hydrologic and meteorologic factors for the entire river system.

Acknowledgments--For Figure 1 the author is indebted to G. Schneider of the Freiburg Waterways Office, Freiburg, Germany; and for Figures 2 and 3, to A. Kirchgaessner, Minister of Agriculture of South Baden, Germany.

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ON THE LONGITUDINAL PROFILE OF THE GRADED RIVER

Eiju Yatsu

Abstract--After examining the longitudinal profiles and the grain-size distribution of fluviatile deposits of nine main rivers in central Japan, graded profile is concluded not to be an exponential curve which has been considered as the most adequate description up to the present. It is due to the discontinuity of wearing out of bed load, that is to say, the sediments of two to four mm in grain size are not easily produced and therefore comparatively of smaller quantity.

Introduction--Several decades ago, the conception of graded river was introduced into geomorphology and a great number of investigations and debates on the longitudinal profile of graded rivers have been made by civil engineers and geomorphologists. However, complete agreement has not been reached in these works, and therefore, the author has investigated the profiles of lower courses of main rivers in central Japan.

Data relating to the Joganji, Sho, Nagara, Kiso, Tenryu, Abe, Yahagi Rivers in the Chubu District and the Kinu and Watarase Rivers in the Kwanto District are given by the Department of Construction (see location map, Fig. 1). Various data concerning sediments of these rivers presented herein are collected for the most part through the author's effort and the grain-size distribution is expressed in ϕ scale.

Longitudinal profile of graded rivers--The conception of graded rivers was reviewed in detail by BAULIG [1925], KESSELI [1941], WOODFORD [1951], and Others. A river is at grade with the attainment of an equilibrium between energy of the water and resistance of the bed (after A. Surell and M. Dausse), or between the power and the load [after GILBERT, 1877, and his followers]. Exactly speaking, though the precise balance will not be unquestionably maintained as KESSELI [1941] asserts, the graded river has a smooth-curve profile and seems to be fairly stable as it approaches maturity in the cyclic development according to DAVIS [1902]. Thus the graded river is a system in equilibrium: its diagnostic characteristic is that any change in any of the controlling factors will cause displacement of the equilibrium in a direction that will tend to absorb the effect of the change as demonstrated by MACKIN [1948].

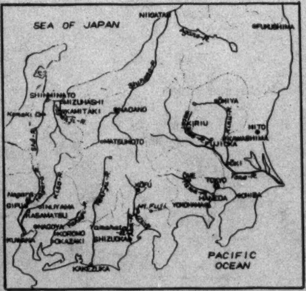

Fig. 1--Sketch map showing the main rivers in central Japan

What shape has the graded river? Taylor concluded a profile of equilibrium is parabola or hyperbola. JOHNES [1924] introduced a empirical logarithmic curve and GREEN [1934] simplified it. WOODFORD [1951] found Green right and followed his formula. Ordinarily, the exponential curve has been admitted to be most appropriate [STERNBERG, 1875; EXNER, 1922; FORCHHEIMER, 1930; SCHOKLITSCH, 1937; SHULITS, 1941; and AKI, 1941]. Recently STRAHLER [1952] showed it as an exponential function of two variables, the time and the distance from streamhead along the river course.

In order to scrutinize these theories, the writer selectively examines the profiles of main rivers in central Japan, whose lower courses have neither tributaries nor distributaries and so may be regarded as graded rivers.

Figures 2-10 show the mean lowwater levels or the water levels observed simultaneously in lieu of the former, and the lowest longitudinal profiles of the rivers drawn by connecting the deepest points of cross sections.

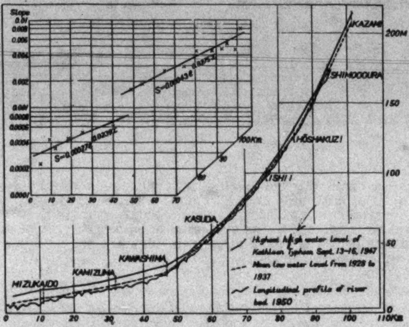

Fig. 2--Longitudinal profile of Kinu River

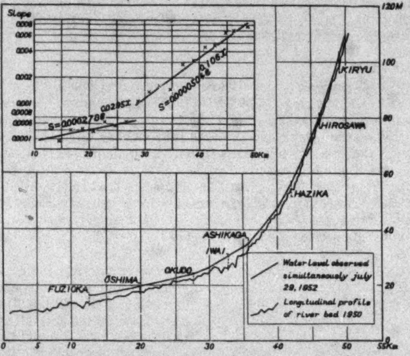

Fig. 3--Longitudinal profile of Watarase River

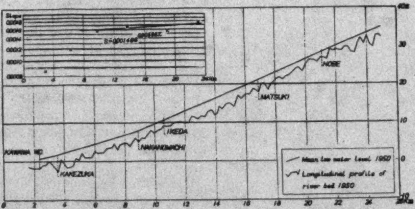

Fig. 4--Longitudinal profile of Tenryu River

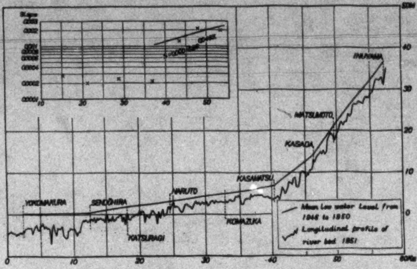

Fig. 5--Longitudinal profile of Kiso River

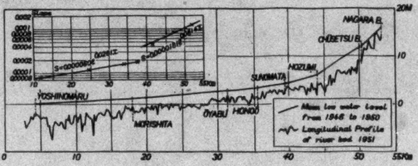

Fig. 6--Longitudinal profile of Nagara River

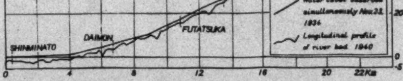

Fig. 7--Longitudinal profile of Sho River

As the Joganji River has neither data of mean water level nor simultaneous water level, the mean altitude of the river bed calculated from cross sections of the river course is expressed. River slopes given on the figures are computed by the method of least squares from the water level or mean altitude of each river bed. Table 1 gives slope data for these nine rivers.

The Yahagi and the Abe Rivers are both distinctly represented by one continuous exponential function of the distance from the river mouth. The other seven rivers, however, have slopes consisting of two exponential curves. If the river slope indicates one exponential curve the longitudinal profile of this river should be exponential because river profile is the integral of the river slope.

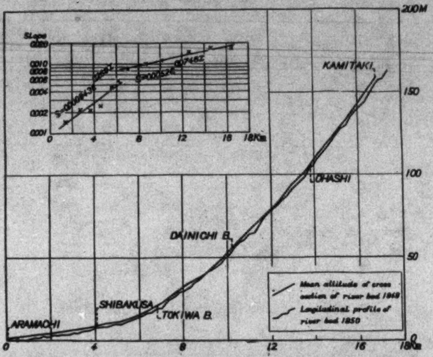

Fig. 8--Longitudinal profile of Joganji River

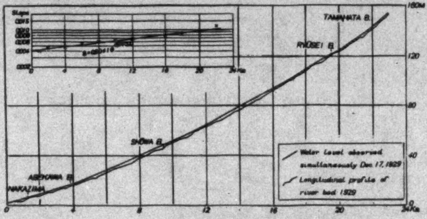

Fig. 9--Longitudinal profile of Abe River

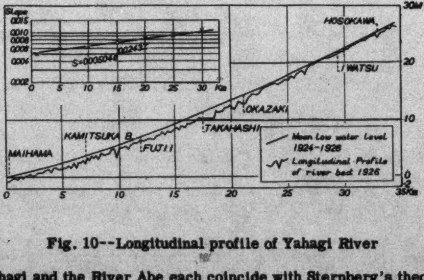

Fig. 10--Longitudinal profile of Yahagi River

Thus, the River Yahagi and the River Abe each coincide with Sternberg's theory but the other rivers do not. Is such discrepancy due to the fact that these seven rivers might not yet have attained maturely graded conditions?

Table 1--Data on nine rivers selected for this research

River	Reach[a]	Slope[b]	Locality of slope discontinuity
	km		km
Kinu	0-40	0.00027 exp 0.0239x	40-48
	48-100	0.00043 exp 0.0275x	
Watarase	13-27	0.000278 exp 0.0295x	27-29
	29-50	0.0000504 exp 0.106x	
Tenryu	10-24	0.00149 exp 0.00588x	8
Kiso	40-55	0.000168 exp 0.049x	40
Nagara	4-40	0.000060 exp 0.0281x	40
	40-53	0.0000181 exp 0.0814x	
Sho	4-24	0.00144 exp 0.0713	4
Joganji	0-6	0.00943 exp 0.269x	6
	6-17	0.0052 exp 0.0746x	
Abe	0-23	0.0041 exp 0.043x	none
Yahagi	0-35	0.00504 exp 0.0243x	none

[a] Distance from the river mouth or junction along the river course

[b] x is the distance above the mouth or junction

According to LOBECK (1939) the following observable characteristics of mature streams may be taken to indicate that a graded profile has been established: (a) flood plain, with natural levee, (b) meander, with cut-off and oxbow lakes, (c) width of valley equal to or greater than width of meander belt, (d) no rapids or falls, etc. Judging from these topological criteria, all of these nine rivers have already attained graded conditions. How is this contradiction to be solved?

Perhaps some geomorphologists may assert that these rivers do not show one exponential curve as they flow out over the fans and their bordering alluvial plains so that a discontinuous decrease of slope springs up at the boundaries between fans and alluvial plains. However, the suddenly decreasing points of river gradient do not coincide with the fan margins but distinctly advance farther forward than the latter. The Kiso River shows at least two km of such advance, and the Joganji River three km. Moreover such rivers on the alluvial fans do not intactly flow on them but sculpture them, especially in the vicinities of the apex of the fans, and deposition is always occurring at the margin of the alluvial fans, therefore the river gradients do not always agree with the topography of the fans. Furthermore, even in the case of the obscurity of fan topography, river slope discontinuity of the Kinu River and of the Watarase River is very distinct. That the remarkable border line of the fan margin exists is not the cause for the river slope discontinuity, but rather the slope discontinuity originating in the river seems to be the root for the former.

Nor does it seem correct to conclude that this discontinuous decrease of the river gradient is due to the eustatic movement of sea level or crustal movement and that this slope discontunuity should spring up on the former shore line at the early Holocene transgression. The reason for the above statement is that the points of the slope discontinuity of the Kinu River and of the Watarase River are far away from shell mounds, relics of the prehistoric Japanese Tribes, which indicate the inner limit of the transgression of the early Holocene.

The renovation depth of river deposits by flood is so great (for example, 2.0 m at Kitamatsuno on the Fuji River course [AKI, 1941] by the high flood water level of 8.5 m, and at Kawamata on the Tone River in Kwanto Plain, 1.5 m in depth by the high water level of 3.5 m [ITO, 1934]), that the river course will surely be reduced to a graded stream and that the river will fairly soon attain equilibrium on the unconsolidated material except where there is hard rock. For about a decade, the river bed of the Sho below Komaki Dam has been deepened. It attained stability in 15 years after construction of this dam [AKI, 1951]. This fact is not caused by the long gradual changes such as the crustal movement or changes of sea level.

What then is the reason for such discontinuous decrease of the river slope?

Critique on the theory of equilibrium and discussion of the discontinuity of grain size distribution of fluvial deposits--It is not adequate to enumerate the factors one by one and debate on them seperately, such as discharge, velocity, mass of the load, the form of the cross section, its caliber, etc. which determine the gradient of graded rivers like WOODFORD [1951] and other investigators have done. The most pertinent method is to deal with the balance between the bed load and the tractive shear force which is expressed as follows by P. du Boys in 1879.

$$\tau = \gamma H I$$

where γ is the density of water, H and I are hydraulic depth and slope of river respectively. The formula of KRAMER [1934] for critical shear force τ_0 is defined next as

$$\tau_0 = (100/6)\,(d_m/M)\,(\gamma_1 - \gamma)$$

where τ_0 is the critical shear force in grams per square meter, $(\gamma_1 - \gamma)$ is the effective density of the bed load in grams per cubic centimeter, d_m is a mean grain diameter in millimeters and M is defined as

$$M = \sum_{p\,=\,0\text{ pct}}^{p\,=\,50\text{ pct}} d\,\Delta p \Big/ \sum_{p\,=\,50\text{ pct}}^{p\,=\,100\text{ pct}} d\,\Delta p$$

AKI's [1951] formula is very similar to KRAMER's. Lately the mechanism of entrainment of particles was investigated by O'BRIEN [1934], KALINSKE [1947], and others.

In natural open channels, the fluvial deposit will agree with the tractive force, and in turn the latter will change itself so that it may agree with the debris. For instance, the tractive force in excess of τ_0 will transport debris, the river bed at this place will be deepened as compared with its lower course, and the river slope will gradually decrease as does the tractive force. Such process is termed degradation. Therefore the balance between tractive force and bed loads causes the longitudinal profile of the river to be steady and smooth.

The grain size of debris decreases downstream by attrition. STERNBERG [1875] dealt with a portion of the Rhein which receives relatively little water or bed load from its tributaries. He assumed the reduction in weight of a particle to be directly proportional to the work done overcoming friction in the distance traveled, and he introduced Sternberg's abrasion law which is defined as follows

$$p = p_0\, e^{-c\zeta x}$$

where p is the weight, ζ the coefficient of friction, x the distance traveled, measured positive downstream, c the constant of proportion, and p is p_0 at $x = 0$.

Sternberg's law originated the thought that a graded river has an exponential profile. Assuming that the gradient of many rivers is directly proportional to the particle size, which decreases downstream according to Sternberg's law on a reach of the river receiving no water from tributaries, the exponential longitudinal profile is mathematically deduced. For example, SHULITS [1936, 1941] expressed it as

$$S = \sigma p_0\, e^{-\alpha x}$$

where S is the slope and σ the constant. If $x = 0$, $S = S_0$, so that $\sigma p_0 = S_0$ and $S = S_0 e^{-\alpha x}$. Let Z be the elevation of any point on the profile, then $S = dz/dx$. Integration of this formula yields an exponential curve for longitudinal profile. The slope equation of PUTZINGER [1919] is of nearly the same form.

Does Sternberg's law leave no room for doubt? Sternberg investigated the deposits of the Rhein from Hüningen to Mannheim and found them to consist mainly of gravel. Many works in Japan by MINO [1950], NAKAYAMA [1952], and OTSUKA and YATSU [1948] also recognized that Sternberg's law is legitimate so far as the diameter of grains is greater than the pebble size (four mm). In case of the Tama River, flowing to Tokyo Bay,

$$y = 95.4e^{-0.0192x}$$

in which y is the median diameter of deposits in millimeters and x the distance along the river from Ome in kilometers. And yet it is very noteworthy that the grain-size decrease of the debris from geschiebe to sand is discontinuous and does not obey the exponential equation. This fact was reported by the author [YATSU, 1951, 1952 ab]. In Figure 11 are shown the relations between the distance traveled and the median grain size of sediments of the main rivers in central Japan. On the reaches of the Yahagi and Abe Rivers decreases in the grain size showed an exponential curve because the deposits of the former are almost sandy particles and the median diameter of the deposits of the latter is gravel. When the river course in discussion consists of two parts in which the median diameter is gravelly and sandy respectively, the grain size decreases according to two exponential curves and thus the discontinuity from gravel to sand downstream is very striking as shown on the Figure 11.

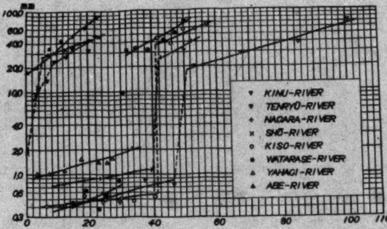

Fig. 11--Median diameter of fluvial deposits and the distance from the river mouth or junction along the river course

In order to explain the cause of the discontinuity of the grain-size clearly, the writer will illustrate the grain-size distribution of fluvial deposits of these rivers. Figures 12-14 give a solution. Let us investigate the distribution of the particle size within an individual sample of deposits. The frequency curves are made graphically from cumulative curves [TWENHOFEL and TYLER, 1941]. While the deposits of sandy materials have only one maximum, the deposits which consist of sand and gravel ordinarily have two maxima and one minimum. This minimum always occurs at the particle size from two to four mm in diameter. Assuming the wearing out of the debris moving downstream to be exponential, the maximum of the frequency would be shifted regularly on the horizontal axis of ϕ -scale from left to right for the ϕ -scale is logarithmic ($\phi = \log \xi$ in which ξ is the diameter of particles), and such a minimum would not be stagnant at the particle size 2-4 mm. The debris of such particle size seems to be produced rarely since the pebble has a tendency to be crushed into individual minerals. Thus the concept of discontinuity of wearing out of the debris from gravel to sand has, of course, to be admitted. Naturally, the difference of rocks, such as in mineral size and hardness, seems to cause the discontunuity of size to vary to some degree. For example, a particle has a minimum of about eight mm if the deposits consist of the granitic debris as in the Yahagi River.

In such a manner, the quantity of granules is relatively small because of the discontinuous wearing of the debris. This is the cause for the fact that the seven rivers with the exception of the Yahagi and Abe Rivers have profiles represented not by one but by two segments. The Abe River transports gross materials to the river mouth, but the course of the Yahagi River under consideration is replete only with coarse sand. Therefore these two rivers indicate no discontinuous decrease of river gradient on the longitudinal profile. The Mississippi River from Baton Rouge to Cairo investigated by SHULITS [1941] has an exponential longitudinal profile, for, the writer thinks, this river course has deposits from coarse sand to silt [RUSSELL and TAYLOR, 1937].

Conclusion--If a river attains the graded state by degradation or aggradation, its longitudinal profile has a portion of discontinuous decrease of stream gradient and will be divided into two ex-

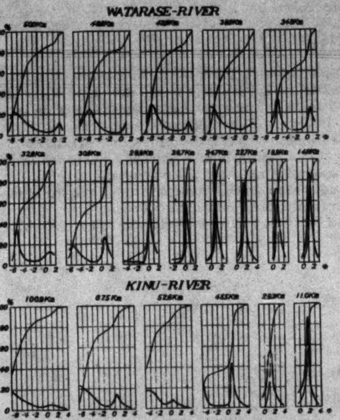

Fig. 12--Cumulative-frequency curves with class units in phi terms of the deposits of the Watarase and Kinu; y-axis expresses the weight percentage; Sampling localities are indicated on each graph by the distance along the river course from the river mouth or junction

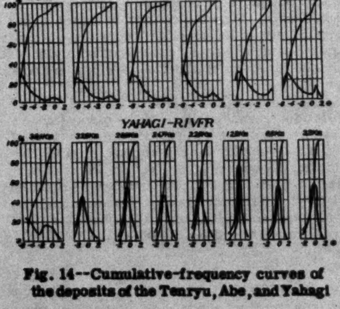

Fig. 14--Cumulative-frequency curves of the deposits of the Tenryu, Abe, and Yahagi

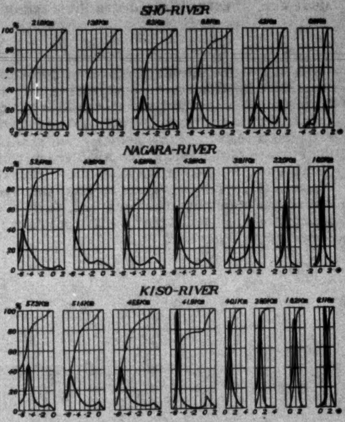

Fig. 13--Cumulative-frequency curves of the deposit of the Sho, Nagara, and Kiso Rivers

ponential curves, because of the discontinuous collapse at the grain size from two to four mm which seems to occur in streams. Sternberg's law is correct on the river course, deposits of which are only gravelly or only sandy and silty.

The distinct boundary limits between fans and their bordering alluvial flat plains also seem to be due to the discontinuous collapse of the debris.

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FREE-SURFACE FLOW TOWARD PARTIALLY PENETRATING WELLS

Mladen Boreli

Abstract--By means of the relaxation technique, both the form of the free surface and the characteristics of flow have been determined for a systematically selected series of wells that partially penetrate a homogeneous aquifer. The computed rates of discharge are compared with rates indicated by existing formulas, such as those of Kozeny and Forchheimer, the errors of which are sometimes quite large. An improved formula is presented.

Introduction

Analyses of partially penetrating wells have been undertaken by many hydraulicians, among the best known of whom may be cited THEVENET [1884], CLAVENAD [1890], Brouchon, PORCHET [1930], Kozeny, FORCHHEIMER [1930], and Babouschkine. Each of these authors has obtained an expression for the discharge in terms of the radius of the well, the distance of the well bottom from the impermeable bed, the depth of water in the well, the permeability and the elevation of the water table at infinity.

The present study has two principal purposes: (1) to analyze critically the existing formulas (particularly those of Kozeny and Forchheimer, which are currently the most utilized), to compare these formulas with the results obtained by the method of relaxation, and eventually to obtain a new formula; and (2) to study the form of the free surface in the neighborhood of the well, which seems never to have been treated with sufficient rigor.

The relaxation method has been used in dealing with the particular cases treated here. As the experience gained in the application of this method has already been published elsewhere [BORELI, 1953], only the results obtained are discussed herein. However, to show the way to approach the general problem, a preliminary analysis is given first. After the results of relaxation are presented, formulas describing these results are devised.

Preliminary analysis

In the following analysis, which will provide a guide to the relaxation calculations, it is assumed throughout that the porous medium is isotropic and characterized completely by the permeability k, and that Darcy's law is valid throughout the domain. It can readily be shown that under these assumptions the flow is determined from a potential satisfying the Laplace equation. Furthermore, it is assumed that the bottom and the wall of the well are permeable to liquids without loss of head, and that the free surface extends from the well to infinity.

Notation--The following notation is used:

t = depth of water in well
s = distance from well bottom to impermeable bed
r = radius of well
Q = discharge
k = permeability
z = height measured from well bottom
h, ρ = coordinates of an arbitrary point on the free surface
H, R = coordinates of a given point on the free surface
H_c, R_c = coordinates of a given point on the free surface at a distance $R_c = Cr$ (C = constant for one particular study)
h_s = height of the seepage point
H_e = $H - s$
h_D = height given by Dupuit's formula
Δh = $(h_D - h)/h_D$

__Dimensional analysis__--If, in addition to the variables t, s, r, and k, the coordinates (R, H) of the point on the free surface are given (see Fig. 1), then the free surface is entirely determined. Thus

$$\phi_1(t, s, r, k, H, R, h, \rho) = 0 \quad . \; . \; . \; (1)$$

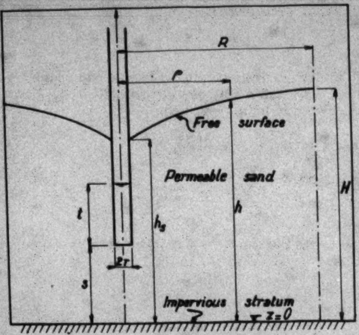

Fig. 1--Definition sketch

(Note that t is depth of water in the well, as shown in Fig. 1). If the free surface extends to infinity, the variables R and H can be replaced by a single variable, say the discharge Q. Thus the number of variables in (1) is reduced by one

$$\phi_2(t, s, r, k, Q, h, \rho) = 0 \quad . \; . \; . \; . \; (2)$$

The variables t, s, r, k, and Q will be designated as the essential variables of the problem. The problem being purely kinematic, the flow depends only on the two fundamental quantities, length and time. A dimensional analysis yields the relationship

$$\phi_3\left(\frac{\rho}{h}, \frac{r}{s}, \frac{t}{s}, \frac{Q}{kr^2}, \frac{r}{\rho}\right) = 0 \quad . (3)$$

among the dimensionless parameters. The principal purpose of this investigation is to determine the function in (3), which will then permit the evaluation of the discharge from the coordinates of an arbitrary point on the free surface. It is obvious that if one could not obtain an exact expression for the free surface, the value of Q would depend on the point (ρ, h) chosen. Thus one can show that Dupuit's formula for wells with bottoms at the impermeable layer

$$\frac{h^2 - t^2}{\ln \rho - \ln r} = \frac{Q}{k\pi} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (4)$$

is not valid in the vicinity of the well, since on taking different points on the free surface determined by the relaxation technique [YANG, 1949] or by the electric analogy [BABBITT and CALDWELL, 1948] one does not arrive at a unique discharge.

Dupuit's formula can be written

$$\frac{H^2 - h^2}{\ln R - \ln \rho} = \frac{Q}{k\pi} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (5)$$

in which (R, H) is a certain arbitrarily chosen point on the free surface. The larger the distance from the well, the more exact (5) becomes. Thus for axisymmetric flow the equation of the free surface should reduce to (5) for sufficiently large radii, and (5) is a limit for (1) and (3) in the most general case. Letting h = H and ρ = R in (3), one has

$$\phi_3\left(\frac{R}{H}, \frac{r}{s}, \frac{t}{s}, \frac{Q}{kr^2}, \frac{r}{R}\right) = 0 \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (6)$$

Equations (3) and (6) yield, on elimination of t/s

$$\phi_4\left(\frac{r}{s}, \frac{Q}{kr^2}, \frac{\rho}{h}, \frac{\rho}{r}, \frac{R}{H}, \frac{r}{R}\right) = 0 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (7)$$

which evidently has one more parameter than (3). Upon rearrangement, (7) assumes the form

$$\phi_5\left(\frac{r}{h}, \frac{r}{R}, \frac{s}{\rho}, \frac{Q}{kh^2}, \frac{H}{h}, \frac{\rho}{R}\right) = 0 \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (8)$$

Equation (8) reduces to the equation of Dupuit, if the explicit effects of r/h, r/R, and s/ρ are negligible. Under such conditions (8) becomes

$$\phi_6\left(\frac{Q}{kh^2}, \frac{H}{h}, \frac{\rho}{r}\right) = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

which is essentially (5), the equation of Dupuit.

As has been stated, the principal purpose of this study is to obtain a relationship of the type of (3) for the free surface and the discharge. This relationship may be very complicated. However, the fact that one knows its limiting form a priori may be a great help.

Equation (3) can be written in a slightly different form

$$\phi_7\left(\frac{t}{h}, \frac{s}{h}, \frac{r}{h}, \frac{Q}{kh^2}, \frac{\rho}{r}\right) = 0 \quad \ldots\ldots\ldots\ldots\ldots (10)$$

Defining H_c as the reference height corresponding to the radius $R_c = Cr$, in which C is a constant, one can simplify (10) to the form

$$\phi_8\left(\frac{t}{H_c}, \frac{s}{H_c}, \frac{r}{H_c}, \frac{Q}{kH_c^2}, C\right) = 0 \quad \ldots\ldots\ldots\ldots\ldots (11)$$

which permits the evaluation of Q once r, s, t, H_c, and C are given. It will be supposed that the point (R_c, H_c) is located in a domain where the free surface can be expressed in a simple manner; for instance, by (9)

$$\phi_6\left(\frac{Q}{kh^2}, \frac{H_c}{h}, \frac{\rho}{R_c}\right) = 0 \quad \ldots\ldots\ldots\ldots\ldots (12)$$

in which ρ and h are the coordinates of a point on the free surface in the domain under consideration.

Equation (12) permits the determination of H_c corresponding to a sufficiently large value of R_c if ρ and h are given. The value of H_c, when substituted in (11), gives the discharge for an arbitrary point (ρ, h) on the free surface. In practice, however, since (11) is rather complicated, it is more convenient to keep (11) and (12) in the present parametric form, with H_c as the parameter.

Criticism of the classical formulas--The formula of FORCHHEIMER [1930]

$$\frac{Q}{k\pi} = \frac{H^2 - (t+s)^2}{2.3\log(R/r)} \sqrt{\frac{t + 0.5r}{t+s}} \sqrt[4]{\frac{2s+t}{t+s}} \quad \ldots\ldots\ldots\ldots (13)$$

and that of Kozeny

$$\frac{Q}{k\pi} = \frac{H_e^2 - t^2}{2.3\log(R/r)}\left[1 + 7\left(\frac{r}{2H_e}\right)^{1/2} \cos\frac{\pi H_e}{2H}\right] \ldots\ldots\ldots (14)$$

give only an approximate expression for the free surface in the form of an equation of the type of (11), as one can easily see by putting H equal to h. In fact, the study has shown that, beyond a certain abscissa, the law of Dupuit is verified with a great precision. Now the formula of Forchheimer cannot be reduced to that of Dupuit. As to the formula of Kozeny, it attributes to the variables s, t, and r too great an influence - beyond that abscissa for which the law of Dupuit is well verified. Thus (13) and (14) cannot be correctly reduced to the type of (9).

Even if one could choose a point around which the formulas of Forchheimer and of Kozeny are well verified, the free surfaces given by these formulas would still differ from the actual free surface at a point sufficiently distant from the reference point (R_c, H_c) by an amount depending on the choice of this point. Forchheimer and Kozeny did not indicate the values they chose for R and H. Consequently, the precision of their formulas should vary according to the position of the reference point.

Choice of cases for relaxation--The parametric equations of the free surface will be utilized in the study, and R_c will be taken to be 112 r. The complicated problem of partially penetrating wells cannot be solved purely theoretically with the mathematical tools available at present. Only experimental or approximate numerical methods can furnish the results.

Since it would demand a prohibitively large amount of work to cover the whole domain of the three independent parameters t/H, s/H, and r/H, one is obliged to choose a finite number of points in the space of these parameters to cover as large a domain of interest as possible. At least seven points forming approximately a 'star' in the parameter space must be chosen (the method of the cube), as shown in the second to fifth columns of Table 1.

Table 1--Magnitudes of parameters chosen for relaxation solutions, and corresponding errors of Kozeny's, Forchheimer's, and writer's formulas

Case	$\frac{t}{H}$	$\frac{s}{H}$	$\frac{r}{H}$	$\frac{Q}{k\pi H^2}$	ΔQ_K	ΔQ_F	ΔQ_{17}
					pct	pct	pct
1	0.0000	0.2650	0.02208	0.14510	+6.4	-67.0	-1.4
2	0.1730	0.2594	0.02162	0.13439	+9.0	-5.9	+0.7
3	0.3490	0.2618	0.02182	0.11145	+7.9	+1.8	-1.2
4	0.1733	0.2600	0.01083	0.12960	+4.8	-4.0	-0.2
5	0.1713	0.2570	0.04283	0.14677	+10.8	-11.0	-0.0
6	0.1935	0.5206	0.02160	0.05886	+20.0	+4.7	-2.5
7	0.1739	0.0217	0.02174	0.19972	+0.8	+1.9	+0.4
8	0.1739	0.0000	0.02174	0.20548	+0.0	+3.7	0.0

In order to utilize the cube method, it is necessary to have results at points for which the values of two of three dimensionless parameters are those at the center of the cube with the coordinates t/H = 0.1739, s/H = 0.2609, r/H = 0.02174. It can be seen from Table 1 that this condition was not rigorously satisfied, although the values necessary for the cube method and those obtained by the relaxation technique are very close. The transition to the cube points was carried out as follows. At first the discharges were determined for the relaxation points and compared with those obtained by the formulas of Kozeny and Forchheimer. Owing to the proximity of the points, the discrepancies were assumed to be the same at the corresponding cube points too. The correction was performed utilizing the formula of Kozeny in Case 1 and the formula of Forchheimer in all other cases.

Results obtained by relaxation

After the cases to be treated were suitably chosen, the relaxation process was carried out for all except Cases 5 and 7 to a radius R = 112 r, the resulting surface profiles and lines of constant piezometric head being shown in Figure 2. Case 5 involved extrapolation from $\rho/r = 56$ to $\rho/r = R/r = 112$ according to (5). In Case 7 (Fig. 2g) the principal purpose was to study the potential field for a small value of s, and the method of relaxation was applied only in the vicinity of the well bottom. The quantity R_c/r was taken to be 112 throughout the calculations. The results obtained are presented in the following sections.

Discharge rates--Since, as will be shown, the errors of the two formulas most often employed at present to calculate the discharge are quite large, it is deemed advisable to establish a new formula on the basis of the present results.

To express the discharge, the type of formula has been taken to be that of Kozeny (with R_c = 112 r)

$$\frac{Q}{k\pi} = \frac{H_e^2 - t^2}{\ln R - \ln r}(1 + \Delta q) \quad \ldots\ldots\ldots\ldots\ldots \quad (15)$$

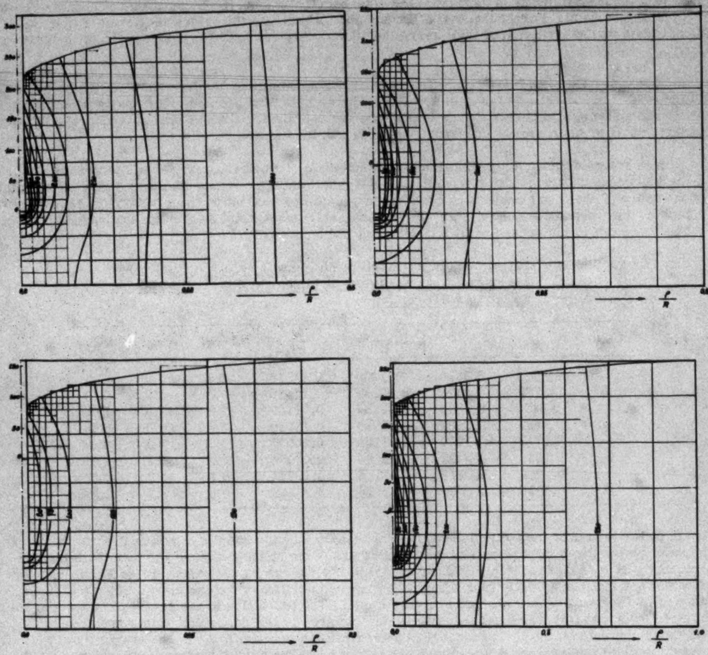

Fig. 2--Relaxation solutions; arbitrary numerical scale on ordinates and equipotentials; left-hand line in each case indicates axis of well: (a) Case 1; (b) Case 2; (c) Case 3; (d) Case 4

Equation (15) has several advantages:

(1) It has a very clear physical significance. The quantity Δq is proportional to the change in discharge with increasing thickness of the aquifer; that is, increasing s with H_e constant. This change is caused partly by the additional discharge which serves the well at the bottom, and partly to the increase in discharge through the vertical wall of the well as a result of the accentuated curvature of the potential lines in the vicinity of the singular point (r, s). It is interesting to note that, as $r \rightarrow 0$, Δq does not approach zero, whereas it vanishes in Kozeny's formula.

(2) It allows certain boundary conditions to be satisfied in a very simple manner. For instance, for $t = H_e$, the discharge vanishes for any value of s.

(3) The function Δq has fewer conditions to satisfy and can thus be simpler. Moreover, the errors which are quite large for Δq may have a much less marked effect on Q ($\Delta q < 1$).

From the relaxation results,

$$\begin{aligned} \Delta q\ (t/H) &= 0.234 \text{ for Cases 1, 2, 3} \\ \Delta q\ (s/H) &= 0.511 \sin (1.8\ s/H) \text{ for Cases 2, 6, 8} \qquad \ldots\ldots\ldots (16) \\ \Delta q\ (r/H) &= 0.132 + 4.68 \sin (1.8\ s/H) \text{ for Cases 2, 4, 5} \end{aligned}$$

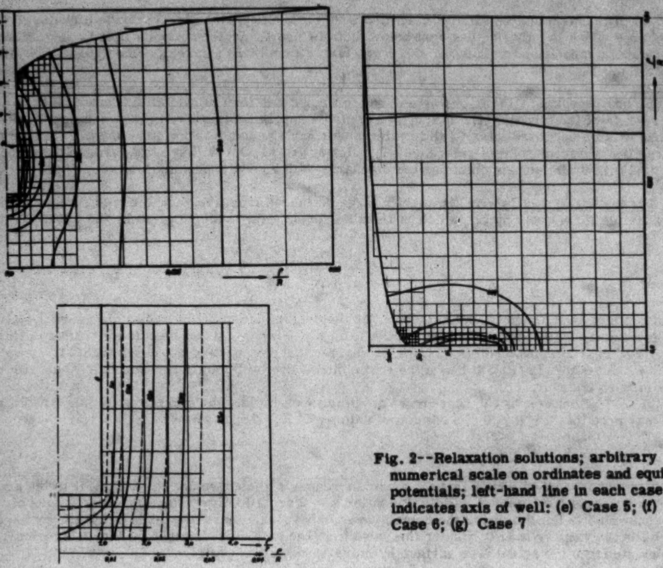

Fig. 2--Relaxation solutions; arbitrary numerical scale on ordinates and equipotentials; left-hand line in each case indicates axis of well: (e) Case 5; (f) Case 6; (g) Case 7

one obtains

$$\frac{Q}{k\pi} = \frac{H_e^2 - t^2}{2.3 \log (R/r)} \left[1 + \left(0.30 + 10 \frac{r}{H} \right) \sin \left(1.8 \frac{s}{H} \right) \right] \quad \ldots\ldots\ldots (17)$$

in which $R = R_c = 112\,r$.

For $t/H \to 0$, in (16) the increase in curvature of potential lines in the vicinity of the singular point (r, s) should increase Δq. For $t = 0$, approximately $\Delta q = 0.258$ was obtained. But the value 0.234 was taken, because, in the first place, there results a difference in discharge of the order of two per cent, and, in the second place, the importance of the phenomenon which causes the augmentation of discharge should decrease with decreasing depth. In practice, of course, there must always be a finite depth for the purpose of pumping.

Although (17) was obtained from the eight cases treated and hence, at first sight, can be expected to be valid only in the domain covered by the eight points in the space of t/H, s/H, and r/H, closer examination shows that the very favorable conditions encountered here permit the use of extensive extrapolations:

(1) The extrapolation to very large values of t/h is extremely accurate, since Δq does not depend on t/h.

(2) The extrapolation for $s/H \to 1$ is equally accurate for analogous reasons. In fact, in Case 6 the quantity $\sin(1.8\ s/H)$ already has a value of 0.805 and the curve of Δq considered as a function of s/H should have a nearly horizontal tangent when $s/H = 1$. In view of the large errors of the formulas of Forchheimer and Kozeny (see Case 6), one can expect that, at least up to $s/H = 0.9$, (17) should be more precise than these two formulas.

(3) The extrapolation for $r = 0$ is also very convenient, since for $r \rightarrow 0$ the formula gives a discharge which is only five per cent below that of Case 4. On the other hand, it is not advisable to try an extrapolation to values of r/H much larger than that in Case 5. Thus (15) will be limited by $2r/H < 0.1$.

Strictly speaking, (17) is only one of the two equations for the rate of discharge, with $R = R_c = 112\,r$. It is of the type of (11). In fact, it is only by supplementing it with (12) or a corresponding formula (to be specified later), valid in the domain under consideration, that one can find the discharge if a different point of reference ($R \neq R_c$) is given. One will see that, around the point $R = 112\,r$, (17) is sufficient for obtaining the discharge with a good approximation.

Free-surface profile--At sufficiently large distances from the well, the free surface has a very simple form given by (9), which is Dupuit's formula (h_D = depth given by the latter formula)

$$h_D = \left(H^2 - \frac{Q}{k\pi} \ln \frac{R}{\rho}\right)^{1/2} \qquad (18)$$

The first step of the study should evidently be the determination of the radial distance beyond which this formula is valid. With Δh denoting the ratio $(h_D - h)/h_D$, it has been found from a certain number of characteristic points on the free surface that, for each of the cases treated,

(1) $\partial \Delta h/\partial(\rho/R) < 0$; hence the error introduced by Dupuit's formula increases with the proximity to the well.

(2) $\partial \Delta h/\partial(\rho/h) < 0$; moreover, Δh diminishes rapidly for increasing radius - depth ratio. One may note that for $s = 0$ the domain of validity of Eq. (18) is given by $\rho/h > 1.5$.

(3) $\partial \Delta h/\partial(t/h) < 0$.

(4) $\partial \Delta h/\partial(s/h) < 0$.

The last inequality shows that the error increases with decreasing s. In fact, it is the greatest for $s = 0$. Thus the limits of validity given for $s = 0$ are a fortiori those for other values of s and are consequently the limits for the domain under study. One therefore takes $\rho/h > 1.5$ as the condition for the validity of (18). Under this condition, the free surface given by Dupuit's formula does not deviate from the actual free surface by more than one per cent.

For $\rho/h < 1.5$, a new formula must be given. For comparison with the function C_x of BABBITT and CALDWELL [1948, p. 30], the quantity

$$\Gamma = \frac{\left[1 - 0.8\left(\frac{s}{H}\right)^{1.5}\right]\left(1 - \frac{h}{H}\right)}{2.3\,\frac{Q}{k\pi H^2}\,\log\frac{10R}{H}} \qquad (19)$$

which reduces to C_x for $s = 0$, is used. The free surface is determined if an expression involving ρ/R is found for Γ. The results of relaxation show that the free surface can be represented as follows.

For $0.3 < \rho/h < 1.5$ one has

$$\Gamma = 0.3 \log \frac{R}{\rho} \qquad (20)$$

and for $\rho/h < 0.3$, which represents the region in the close neighborhood of the well, the expression for Γ is much more complicated and has the form

$$\Gamma = \bar{C}_x + \Delta C \qquad (21)$$

in which

$$\bar{C}_x = 0.3 \log \frac{R}{\rho} - 0.065 \log^2 \frac{R}{10\rho} \quad \text{. . . . .(22)}$$

differs only slightly from the function C_x of Babbitt and Caldwell, and

$$\Delta C = \frac{s}{h}\left[\left(\log \frac{R}{10\rho}\right)\left(1.2\frac{s}{H} - 0.48\right) + 0.6 \log\left(2.4\frac{H}{R}\right) \log \frac{R}{34\rho}\right] \quad \text{. . .(23)}$$

The seepage point can be obtained easily from (17), (19), and (20) by introducing $\rho/R = r/R$. Naturally, near this point the net must be refined several times to yield significant results. In fact, the vicinity of this point has been treated separately, as shown in Figure 3 for Case 5.

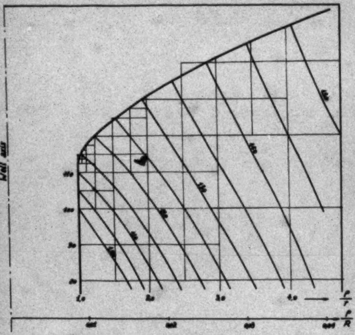

Fig. 3--Potential field in the vicinity of the seepage point for Case 5

Equations (20) - (23) are valid only for $s/H < 0.6$. Let us now write down (8), after rearrangement, as follows

$$F\left(\frac{r}{H}, \frac{s}{H}, \frac{s}{R}, \frac{R}{H}, \frac{\rho}{H}, \frac{Q}{kH^2}\right) = 0 \quad (24)$$

This represents the generalized form of (20) - (23) for the free surface, since in (20) - (23) $r = R/112$. The free surface given by (19) and (20) in the region $0.3 < \rho/h < 1.5$ shows that this zone is a transition between Dupuit's zone and that in the immediate vicinity of the well. In this transition zone only the parameter s/H has an explicit influence on the free surface, while the others can be neglected.

One may point out an interesting agreement between the present results and those of Caldwell and Babbitt. They found that for wells with bottom at the impermeable layer C_x is a function of R/ρ only. For a partially penetrating well the function Γ may depend, in general, on all dimensionless terms of (24). Equations (20) - (23), however, show that Γ is in all regions independent of the quantity Q/kH^2, which is in conformity with the results of Caldwell and Babbitt. This accordance represents at the same time an indirect verification of both the present results obtained by the relaxation technique and theirs achieved by the electrical analogy.

Comparison with classical formulas--The percentage error for the discharge Q_K according to Kozeny's formula is definied as

$$\Delta Q_K = 100\,(Q_K - Q_e)/Q_e$$

in which Q_e is the discharge obtained by relaxation. The percentage error ΔQ_F for the discharge Q_F according to Forchheimer's formula is similarly defined. From Table 1, in which these percentage errors are tabulated, it can be seen that ΔQ_K and ΔQ_F can be quite large. The superiority of (17) to the formulas of Forchheimer and Kozeny is clearly demonstrated by the relative magnitudes of the last three columns in the same table, in which ΔQ_{17} stands for the percentage error committed by applying Eq. (17).

As to the free surface, it has been shown in the preceeding section that for $\rho/h > 1.5$ the formula of Dupuit (18) gives a good approximation. For $\rho/h < 1.5$, no previous results are sufficiently significant to be used as a basis for comparison.

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USE OF HYDROCHEMISTRY AND TEMPERATURE OF UNDERGROUND WATERS IN PETROLEUM EXPLORATION: A REVIEW

George V. Chilingar

Abstract--Chemistry and temperature of underground waters appear to be useful tools in petroleum exploration.

Hydrochemical methods of exploration in USSR [SUKHAREV, 1951]--According to SUKHAREV [1951], the hydrochemical methods of exploration are successfully used in USSR. V. A. Sulin [SUKHAREV, 1951] showed that in the hydrocarbonate-sodium type of underground waters a high value of coefficient $k_1 = (rNa^{\cdot} - rCl'): rSO_4''$ is indicative of a high degree of reduction and, therefore, is considered as a favorable indicator for the presence of petroleum. Thus, in cases where the hydrocarbonate-sodium type of waters are highly mineralized ($\Sigma r > 30$-50 mg-equivalents), have high coefficients of reduction, and contain naphthenic acids and such elements as iodine and bromine, the presence of petroleum in the particular formation is very likely.

However, on using the coefficient of reduction (k_1), it is necessary to make a temperature correction. Reduction of sulphates occurs in the presence of sulphate-reducing microorganisms and organic matter, which serves as a nutrient for bacteria. This process can occur at temperatures ranging from 27° to 60°. Although these bacteria can live at temperatures as high as 82° to 88°, they are usually not active at temperatures above 66°, and their maximum activity occurs between 55° and 60°. Therefore, if the temperature of underground waters is below 70°, high k_1 is a favorable indicator, whereas low k_1 will indicate that the particular formation is not likely to be oil-bearing. If temperature is above 70° and k_1 is low, but the underground waters (sulphate-chloride-alkali subgroup) contain naphthenic acids, iodine, and bromine, the presence of petroleum is likely.

Underground waters of calcium chloride type are indicative of well-sealed formations, and, therefore, are favorable indicators of presence of oil. If, in addition, they are highly mineralized ($\Sigma r = 1500$ to 3500 mg-equivalents), and contain increased amounts of alkali earth chlorides, naphthenic acids, iodine, and bromine (without or with small amounts of sulphates), the probability of finding petroleum is very high.

In oil-bearing formations with water circulation, the waters are slightly mineralized and are of hydrocarbonate-sodium type (sulphate-chloride-alkali and chloride-alkali subgroups). In the immediate vicinity of oil deposits the mineralization increases and waters of the sulphate-chloride-alkali subgroup are usually replaced by the chloride-alkali subgroup.

The formations not flushed with water are characterized by calcium chloride types of waters with mineralization of not less than 15 gm/ℓ and, in some cases, as high as 75 to 100 gm/ℓ of dry residue. These waters are radioactive and, as a rule, contain iodine and bromine. Increased concentrations of helium are also characteristic of such waters.

In petroliferous areas the free and dissolved gases associated with ground waters contain heavy hydrocarbons in addition to methane. On going away from petroliferous areas the composition of gases changes from methane to mixtures of methane and nitrogen and finally nitrogen.

Boron-chlorine coefficient in waters of oil-bearing formations [KAZMINA, 1951]--Boron, with iodine and bromine, is usually associated with oil-field brines and is of marine origin. However, due to the tendency toward migration, no one single source can account for its presence. The wide migration of boron can be attributed to the solubility of most of its compounds, and the tendency of boron salts towards hydrolytic dissociation and occlusion, which results in its partial precipitation with other compounds. Some of the possible sources of boron in oil-field brines include (1) sea water, (2) concentration of boron-assimilating organisms in some sediments, (3) mud volcanoes, and (4) presence of disseminated boron aluminosilicates in sediments of various stages of weathering.

Boron remains in sea water until later stages of evaporation, whereas chlorine starts to precipitate from brine as soon as it becomes saturated with sodium chloride (25°-26° Be). The boron-chlorine coefficient ($k_2 = B_2O_3/Cl \times 10^4$) of sea water varies from 8 to 10. M.G. Valiashko [KAZMINA, 1951] plotted on log-log paper k_2 versus the amount of chlorine in oil-field brines from various parts of USSR. A reference curve, showing the variation of k_2 upon evaporation of sea water, clearly shows whether or not k_2 of a particular brine is related to the processes in sea water (evaporation and concentration of salts, etc.) This graph also enables geologists to subdivide brines into genetic groups.

Use of geothermic characteristics in petroleum exploration--SUKHAREV [1951] also showed that in many areas of USSR on approaching the petroleum deposits there is a decrease in temperature of underground waters, although still remaining relatively high in many instances. This can be explained by the fact that waters around the oil deposits are stagnant, and, therefore, are not affected by the encroaching hot waters from below. It is also obvious that horizons devoid of water circulation are more favorable for the preservation of oil and gas.

Conclusions--In drilling the test wells during the petroleum exploration, it is necessary to analyze the underground waters and associated gases (free and dissolved) and measure their temperatures. This may prove to be an invaluable exploration tool. However, it is also necessary to take into consideration the lithologic and structural characteristics of the particular area.

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PROPAGATION OF RAYLEIGH WAVES IN TRANSVERSELY ISOTROPIC MEDIUM IN THREE DIMENSIONS

Sushil Chandra Das Gupta

Abstract--The possibility of propagation of Rayleigh waves has been discussed in transversely isotropic medium. It has been found that the frequency equation is the same as in two dimensional case. It has been shown that in case of ordinary crystals, there is only one real root of the frequency equation which satisfies the necessary boundary conditions.

Introduction--The possibility of propagation of Rayleigh waves in aelotropic medium has been discussed by STONELEY [1949] and SATO [1950]. Both of them have considered only the two dimensional problems, the axis of x being taken in the direction of propagation of waves and the axis of z along the depth. Sato proved in addition that there exists only one root of the frequency equation which satisfies the necessary boundary conditions under assumptions which are unlikely to occur in nature. In this paper, the propagation of Rayleigh waves in a transversely isotropic medium considered as a three dimensional problem has been discussed. The axis of the elastic symmetry as illustrated by crystals of hexagonal system is taken along the vertical line. It is found that the frequency equation in this case reduces to the same expression as in the papers of Stoneley and Sato. By suitable modification of elastic constants results obtained by LAMB [1904] in the case of isotropy can easily be deduced. Further it has been shown that there are three roots of the frequency equation one of which satisfies the necessary conditions.

Basic equations for a medium with transverse isotropy--Taking the axis of z along the vertical line, that is, along the axis of elastic symmetry we can write the stress-strain relations in the case of transverse isotropy as follows

$$\left.\begin{aligned}\sigma_{xx} &= c_{11}\, e_{xx} + c_{12}\, e_{yy} + c_{13}\, e_{zz}\\ \sigma_{yy} &= c_{12}\, e_{xx} + c_{11}\, e_{yy} + c_{13}\, e_{zz}\\ \sigma_{zz} &= c_{13}\, (e_{xx} + e_{yy}) + c_{33}\, e_{zz}\\ \sigma_{yz} &= c_{44}\, e_{yz}, \quad \sigma_{zx} = c_{44}\, e_{zx}\\ \sigma_{xy} &= (1/2)\,(c_{11} - c_{12})\, e_{xy}\end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (1)$$

where $c_{11}, c_{12}, c_{13}, c_{33}, c_{44}$ are elastic constants.

The equations of motion are

$$\left.\begin{aligned}\partial\sigma_{xx}/\partial x + \partial\sigma_{xy}/\partial y + \partial\sigma_{xz}/\partial z &= \rho\,\partial^2 u/\partial t^2\\ \partial\sigma_{xy}/\partial x + \partial\sigma_{yy}/\partial y + \partial\sigma_{yz}/\partial z &= \rho\,\partial^2 v/\partial t^2\\ \partial\sigma_{xz}/\partial x + \partial\sigma_{yz}/\partial y + \partial\sigma_{zz}/\partial z &= \rho\,\partial^2 w/\partial t^2\end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (2)$$

substituting the results (1) into (2) we get from the usual expressions for strain components in terms of displacements

$$c_{11}\,\partial^2 u/\partial x^2 + (1/2)\,(c_{11} - c_{12})\,\partial^2 u/\partial y^2 + c_{44}\,\partial^2 u/\partial z^2 + (\partial/\partial x)\ (1/2)\,(c_{11} + c_{12})\,\partial v/\partial y$$
$$+ (c_{13} + c_{44})\,\partial w/\partial z = \rho\,\partial^2 u/\partial t^2 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$(1/2)(c_{11} - c_{12})\,\partial^2 v/\partial x^2 + c_{11}\,\partial^2 v/\partial y^2 + c_{44}\,\partial^2 v/\partial z^2 + (\partial/\partial y)\Big\{(1/2)(c_{11} + c_{12})(\partial u/\partial x) + (c_{13} + c_{44})\,\partial w/\partial z\Big\} = \rho\,\partial^2 v/\partial t^2 \ldots\ldots\ldots \quad (4)$$

$$c_{44}\,(\partial^2 w/\partial x^2 + \partial^2 w/\partial y^2) + c_{33}\,\partial^2 w/\partial z^2 + (c_{13} + c_{44})(\partial/\partial z)(\partial u/\partial x + \partial v/\partial y) = \rho\,\partial^2 w/\partial t^2 \ldots\ldots\ldots \quad (5)$$

Solution--For solutions of (2), (3) and (4) we put

$$u = \partial\phi/\partial x + \partial^2\chi/\partial x\partial z, \quad v = \partial\phi/\partial y + \partial^2\chi/\partial y\partial z, \quad w = \partial\phi/\partial z + \partial^2\chi/\partial z^2 + K\chi \ldots \quad (6)$$

where K is a constant to be chosen suitably. Then we have from the equations of motion

$$(\partial/\partial x)\Big\{c_{11}(\partial^2\phi/\partial x^2 + \partial^2\phi/\partial y^2) + (2c_{44} + c_{13})\,\partial^2\phi/\partial z^2\Big\} + (\partial^2/\partial x\partial z)\Big\{c_{11}(\partial^2\chi/\partial x^2 + \partial^2\chi/\partial y^2) + (2c_{44} + c_{13})\,\partial^2\chi/\partial z^2 + K(c_{13} + c_{44})\chi\Big\}$$
$$= \rho(\partial^2/\partial t^2)(\partial\phi/\partial x) + \rho(\partial^2/\partial t^2)(\partial^2\chi/\partial x\partial z) \ldots\ldots\ldots \quad (3a)$$

$$(\partial/\partial y)\Big\{c_{11}(\partial^2\phi/\partial x^2 + \partial^2\phi/\partial y^2) + (2c_{44} + c_{13})\,\partial^2\phi/\partial z^2\Big\} + (\partial^2/\partial y\partial z)\Big\{c_{11}(\partial^2\chi/\partial x^2 + \partial^2\chi/\partial y^2) + (2c_{44} + c_{13})\,\partial^2\chi/\partial z^2 + K(c_{13} + c_{44})\chi\Big\}$$
$$= \rho(\partial^2/\partial t^2)(\partial\phi/\partial y) + \rho(\partial^2/\partial t^2)(\partial^2\chi/\partial y\partial z) \ldots\ldots\ldots \quad (4a)$$

$$(\partial/\partial z)\Big\{(2c_{44} + c_{13})(\partial^2\phi/\partial x^2 + \partial^2\phi/\partial y^2) + c_{33}\,\partial^2\phi/\partial z^2\Big\} + (\partial^2/\partial z^2)\Big\{(2c_{44} + c_{13})(\partial^2\chi/\partial x^2 + \partial^2\chi/\partial y^2) + c_{33}\,\partial^2\chi/\partial z^2\Big\} + K\Big\{c_{44}(\partial^2\chi/\partial x^2 + \partial^2\chi/\partial y^2) + c_{33}\,\partial^2\chi/\partial z^2\Big\} = \rho(\partial^2/\partial t^2)(\partial\phi/\partial z)$$
$$+ \rho(\partial^2/\partial t^2)(\partial^2\chi/\partial z^2) + K\rho\,\partial^2\chi/\partial t^2 \ldots\ldots\ldots \quad (5a)$$

Let u, v, w be proportional to e^{ipt} and suppose

$$\varphi = RJ_0(\alpha r)\,e^{-\alpha qz}$$

$$\chi = SJ_0(\alpha r)\,e^{-\alpha qz}$$

$$K = [c_{11}/(c_{13} + c_{44})]\alpha^2, \quad p^2/\alpha^2 = c^2$$

where R, S, α, q are constants and q is positive, r standing for $\sqrt{x^2 + y^2}$.

Remembering that $\partial^2/\partial x^2 + \partial^2/\partial y^2 = \partial^2/\partial r^2 + (1/r)\,\partial/\partial r$ we find that (3a) and (4a) are satisfied if

$$R\Big\{-c_{11} + (2c_{44} + c_{13})q^2 + \rho c^2\Big\} = S\Big\{(2c_{44} + c_{13})q^2 + \rho c^2\Big\}\alpha q \ldots\ldots \quad (6)$$

Also (5a) is satisfied if

$$R\Big\{(2c_{44} + c_{13}) - c_{33}q^2 - \rho c^2\Big\}\alpha q = S\Big[\Big\{(2c_{44} + c_{13}) - c_{33}q^2\Big\}q^2 + c_{11}c_{44}/(c_{13} + c_{44}) - [c_{11}c_{33}/(c_{13} + c_{44})]q^2 - \rho c^2 q^2 - \rho c^2 c_{11}/(c_{13} + c_{44})\Big] \ldots\ldots \quad (7)$$

Eliminating R, S from (6) and (7) we get,

$$[\rho c^2 - c_{11} + (2c_{44} + c_{13})q^2]\Big[\Big\{(2c_{44} + c_{13}) - c_{33}q^2\Big\}q^2 + c_{11}c_{44}/(c_{13} + c_{44}) - q^2 c_{11}c_{33}/(c_{13} + c_{44}) - \rho c^2 q^2 - \rho c^2 c_{11}/(c_{13} + c_{44})\Big] = q^2\Big\{(2c_{44} + c_{13})q^2 + \rho c^2\Big\}\Big\{(2c_{44} + c_{13}) - \rho c^2 - c_{33}q^2\Big\} \ldots\ldots \quad (8)$$

On simplification we get,

$$q^4 - q^2\left\{c_{11}/c_{44} - [(2c_{44}+c_{13})/c_{44}]\, c_{13}/c_{33} - \rho c^2/c_{44} - \rho c^2/c_{33}\right\} + c_{11}/c_{33}$$
$$(\rho c^2/c_{44} - 1)(\rho c^2/c_{11} - 1) = 0 \; \ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

Let

$$\tau = \rho c^2/c_{44}, \quad c_{11}/c_{44} = \alpha, \quad c_{33}/c_{44} = \beta \quad \text{and} \quad c_{13}/c_{44} = \gamma \; \ldots\ldots \quad (10)$$

Hence from (9) we get, if q_1^2, q_2^2 are the two positive roots

$$\left.\begin{aligned} q_1^2 + q_2^2 &= \left\{-(\beta+1)\tau + \alpha\beta - \gamma^2 - 2\gamma\right\}\Big/\beta \\ q_1^2\, q_2^2 &= (\tau-\alpha)(\tau-1)/\beta \end{aligned}\right\} \ldots\ldots\ldots \quad (11)$$

We have then

$$\left.\begin{aligned} \varphi &= J_0(\alpha r)\left\{R_1\, e^{-\alpha q_1 z} + R_2\, e^{-\alpha q_2 z}\right\} \\ X &= J_0(\alpha r)\left\{S_1\, e^{-\alpha q_1 z} + S_2\, e^{-\alpha q_2 z}\right\} \end{aligned}\right\} \ldots\ldots\ldots\ldots \quad (12)$$

where R_1, R_2, S_1, S_2 are constants. R_1 and S_1, R_2 and S_2 are connected by means of (6), so that

$$R_1 = S_1\,\alpha q_1 m_1, \quad R_2 = S_2\,\alpha q_2 m_2 \qquad \text{where}$$

$$m_1 = [(2c_{44} + c_{13})q_1^2 + \rho c^2]/[(\rho c^2 - c_{11}) + (2c_{44} + c_{13})\, q_1^2] \; \ldots\ldots\ldots \quad (13)$$

and similar expression for m_2.

The boundary conditions $\widehat{rz}$ and $\widehat{zz}$ are each equal to zero at $z = 0$. So that,

$$\widehat{rz} = c_{44}\,(2\,\partial^2\phi/\partial r\partial z + 2\,\partial^3 X/\partial r\partial z^2 + K\,\partial X/\partial r = 0$$

and

$$\widehat{zz} = c_{13}\,(\partial^2\phi/\partial r^2 + (1/r)\,\partial\phi/\partial r + \partial^3 X/\partial r^2\partial z)$$
$$+ c_{33}\,(\partial^2\phi/\partial z^2 + \partial^3 X/\partial z^3 + K\,\partial X/\partial z) = 0$$

at $z = 0$.

Hence the boundary conditions give

$$S_1\left\{2q_1^2(1 - m_1) + c_{11}/(c_{13} + c_{44})\right\} + S_2\left\{2q_2^2(1 - m_2) + c_{11}/(c_{13} + c_{44})\right\} = 0$$
$$S_1\left\{q_1^3(m_1 - 1) - m_1 q_1\, c_{13}/c_{33} + \left(c_{13}/c_{33} - c_{11}/(c_{13} + c_{44})\right)q_1\right\}$$
$$+ S_2\left\{q_2^3(m_2 - 1) - m_2\, q_2\, c_{13}/c_{33} + \left(c_{13}/c_{33} - c_{11}/(c_{13} + c_{44})\right)q_2\right\} = 0$$

Eliminating S_1 and S_2 we get the frequency equation as

$$\left\{2q_1^2(1 - m_1) + c_{11}/(c_{13}+c_{44})\right\}\left\{q_2^3(m_2 - 1) - m_2\, q_2\, c_{13}/c_{33}\right.$$
$$\left. + q_2\left(c_{13}/c_{33} - c_{11}/(c_{13} + c_{44})\right)\right\} = \left\{2q_2^2(1 - m_2) + c_{11}/(c_{13} + c_{44})\right\}$$
$$\left\{q_1^3(m_1 - 1) - m_1\, q_1\, c_{13}/c_{33} + q_1\left(c_{13}/c_{33} - c_{11}/(c_{13} + c_{44})\right)\right\} \ldots \quad (14)$$

On reduction and simplification of equation (14) by substituting values of $q_1^2 + q_2^2$, $q_1^2\, q_2^2$ we get,

$$\tau(\tau - \alpha) = (\beta\tau - \alpha\overline{\beta - \gamma}^2)\, q_1 q_2 \; \ldots\ldots\ldots\ldots\ldots \quad (15)$$

or

$$f(\tau) = (\beta\tau - \alpha\overline{\beta - \gamma}^2)^2(\tau - 1) - \beta\tau^2(\tau - \alpha) = 0 \; \ldots\ldots\ldots \quad (16)$$

This equation is the same as the corresponding equations of Stoneley and Sato.

Discussion of the roots of the frequency equation--SATO [1950] has shown that $c_{11}>0$, $c_{33}>0$, $c_{44}>0$, $c_{11}>c_{12}$, and $\{c_{11} - (1/2)(c_{11} - c_{12})\} c_{33}>c_{13}^2$ so that $c_{11} c_{33}>c_{13}^2$. Dividing by c_{44} we get $\alpha>0$, $\beta>0$, $\alpha\beta>\gamma^2$. The following data given by Voigt [LOVE, 1920] for Beryl will also illustrate it.

$$c_{11} = 2.694 \times 10^{12}$$

$$c_{33} = 2.363 \times 10^{12}$$

$$c_{12} = 0.961 \times 10^{12}$$

$$c_{13} = 0.661 \times 10^{12}$$

$$c_{44} = 0.653 \times 10^{12}$$

Hence we assume $\alpha>1$, $\beta>1$ and γ is nearly 1. Besides these relations we find from (15) that $\tau-\alpha$ and $\beta\tau - (\alpha\beta - \gamma^2)$ must have the same sign. Also from (11) it is found that $\tau - \alpha$ must have the same sign as $\tau - 1$. Again from the first of the relations (11) we get, $-(\gamma + 1)^2 - (\tau - 1) - \beta(\tau - \alpha)$ must be positive. Therefore, τ is less than α. Hence, $\tau - \alpha$, $\tau - 1$ and $\beta\tau - (\alpha\beta - \gamma^2)$ are all negative. From (16)

$$\begin{array}{lll}
f(-\infty) & = -\infty & -\text{ve} \\
f(0) & = -(\alpha\beta - \gamma^2)^2 & -\text{ve} \\
f(1) & = \beta(\alpha - 1) & +\text{ve} \\
f[(\alpha\beta - \gamma^2)/\beta] & = \gamma^2 (\alpha\beta - \gamma^2)^2 & +\text{ve} \\
f(\alpha) & = \gamma^4 (\alpha - 1) & +\text{ve} \\
f(\alpha+\delta) & = \beta\delta \left\{ \beta\delta(\alpha+\delta - 1) + (\alpha+\delta)(\gamma^2 - 1) - \gamma^2 \right\} &
\end{array}$$

By choosing a sufficiently small δ we can make this expression negative on the assumptions that γ^2 is nearly unity.

Approximately we obtain

$$\delta < [\gamma^2 - \alpha(\gamma^2 - 1)]/[\alpha(\beta - 1) + \gamma^2 - 1]$$

whose value is given by Beryl as 0.09.

$$f(+\infty) = +\infty \qquad +\text{ve}$$

Hence, for those hexagonally aelotropic crystals which generally occur on the surface of the Earth, there exist three real positive roots of (16) one lying between o , 1 ; another between α and $\alpha + \delta$, and a third between $\alpha + \delta$, $+\infty$. It may be mentioned here that the value of τ for Beryl is $(0.965)^2$. Hence it is found that the root lying between 0 and 1 satisfies the necessary conditions for such media and justifies the assumptions made.

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AN OBSERVATIONAL STUDY OF THE ORIGIN OF SHORT-PERIOD MICROSEISMS NEAR SAINT LOUIS, MISSOURI

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Abstract--A survey of four years' records of Florissant Wood-Anderson seismographs reveals that the very small, regular, group microseisms of period very near to 0.3 sec occur in storms of quite variable duration, from less than one hour to over 40 hours. By a consideration of gross hourly occurrences, times of storm beginning and ending and of maximum trace displacements, as well as an investigation of many individual cases, a distinct correlation in time is shown to exist between these short-period microseisms at Florissant and increased short-period microbarographic activity recorded by the Macelwane instrument at the same station.

From only the six-hourly surface synoptic maps, it appears that the great majority of the 155 arbitrarily chosen microseismic storms may be associated either with the approach or passage at the station of a cold frontal type discontinuity or both, or with local, nonfrontal convective activity. These relationships, in agreement with findings for the correlated microbarographic oscillations, suggest that local atmospheric turbulence may be a prime factor in the generation of these short period microseisms. Although this microseismic activity usually persists longer in the post- than in the pre-cold frontal period, a study of these microseisms may be useful in predicting cold front passages over land. A few case histories are presented to reveal certain details of the synoptic study, particularily the sequence of microseismic activity during frontal passages.

There is some indication that these correlated short-period microseisms and atmospheric micro-oscillations are truly recorded vibrations of the ground and of the barometric pressure, respectively. That is to say, it appears that the recorded oscillations are not the result of atmospheric micro-oscillations operating directly on the seismometers or microseisms affecting the microbarographs. It seems also indicated that these ground and atmospheric vibrations are not related as cause and effect at some distance from the recording points. However, they may well proceed from a common source.

This study suggests that, with more precise information, combined analyses of these microseisms and micro-oscillations may be useful in elucidating the local turbulent nature of the atmosphere.

Introduction

About 1930, Macelwane made note of the small amplitude, very regular, and short-period (about 0.2 to 0.7 sec) oscillations appearing at frequent intervals in the records of the Wood-Anderson seismographs operating at the St. Louis and Florissant stations [RAMIREZ, 1948]. Under contract with the Office of Naval Research, St. Louis University initiated a special research program to investigate the nature and origin of these short-period microseisms, utilizing specially designed high magnification capacitance-bridge type seismometers arranged in a small tripartite network [MACELWANE and Others, 1948].

Before final testing of the above system was completed, it was thought useful to study these short-period microseisms by making use of the many years of records from the Wood-Anderson seismographs operating at Florissant and at St. Louis. The purpose of this paper is to present some conclusions as to the origin of this band of microseisms based on a critical examination of their occurrences on the Wood-Anderson records.

Although similar microseisms are recorded rather regularily at many stations, particularily those employing short-period Benioff and Wood-Anderson instruments, this appears to be the first detailed study of their origin. The majority of previous investigators have pointed to traffic and industrial disturbances as prime causative factors of disturbances near this period.

Method and limitations

Seismological data for this study were obtained from the Wood-Anderson records from Florissant and St. Louis for the years 1948 through 1951, with supplementary data from 1952. The data consisted essentially of (1) beginning and ending times of the activity, (2) descriptive characterization of this activity as a whole, (3) time of occurrence of the maximum amplitude, (4) N-S and E-W trace components of this maximum, and (5) recorded periods of this maximum. In specially selected cases hourly microseismic activity values were obtained. By this was meant an average of the three largest, double-amplitude, trace displacements occurring within each hour. Though several other sampling methods were attempted, this was judged sufficiently representative of the variations in activity and much less tedious than other methods.

By individual and gross time comparisons, it will be shown that these short-period microseisms near St. Louis are apparently associated with a particular meteorological phenomenon. Essential to these comparisons were the six-hourly surface synoptic maps (WBAN and Lambert Field Station) and the records of the Macelwane and Benioff microbarographs operating at Florissant.

The limitations of this study and of the method itself must be noted. First, the ordinary Wood-Anderson instruments cannot be considered optimum for investigating low-amplitude, short-period oscillations. Due to the moderate value of magnification of these instruments and the thickness of the light spot, only microseisms attaining trace amplitudes greater than about 0.25 mm were considered of interest. These limitations undoubtedly introduced some errors in reading the beginning and ending times of the microseismic activity. The 60 mm/min rate of registration used by the Wood-Anderson is not sufficiently rapid to permit accurate determinations of slight period variations. These values were therefore recorded only to the nearest 0.1 sec. Second, it became obvious that unrecorded instrumental changes had occurred throughout the years making direct amplitude comparisons and ground motion studies unfeasible. Third, the synoptic maps were published at six-hour intervals and presented data for St. Louis obtained at the Lambert Field Station, some four miles from the Florissant seismological observatory. Interpolations in time and space were therefore necessary. And finally, this is essentially a single station case history study and is restricted by all limitations involved in such a study.

Description of recorded microseisms

Short-period microseisms at Florissant appear as a fine pattern of ordinarily regular waves, displaying a pronounced group or 'beat' effect, with a characteristic period close to 0.3 sec and with usually very small amplitudes, which at times rise to about three mm. These Florissant microseisms may be separated into two types on the basis of the group character.

The more prominent type or 'short-group' type is characterized by a train of waves of about 40 sec duration. This train is composed of a number of groups, each of about one second duration. In many cases, the central amplitude of each group increases from group to group reaching a maximum near the middle of the train then decreases.

The second or 'long-group' type ordinarily consists of a larger number of very regular waves arranged in groups of two to eight seconds' duration. Again a train or series of connected groups may be discerned, the duration of which is 20 to 70 sec. Typical examples of these two types are reproduced in Figure 1.

Monthly and seasonal distribution

Notation was first made of all obtainable Wood-Anderson records for 1948-1951 which contained short-period microseisms appreciably larger than the thickness of the trace and lasting for about two hours or more. In all, some 1409 records were so studied of which 374 or about 27 pct were found to show these short period microseisms. Thus, at Florissant these microseisms cannot be considered a rarity.

In Table 1 are shown the monthly and seasonal percentages of records judged microseismically active. The values are given as percentages of the total number studied in each month and season for the four year period.

Perhaps of some significance is the distribution with respect to the seasons. For the years studied, these short-period microseisms show a maximum percentage of occurrences (37 pct) in

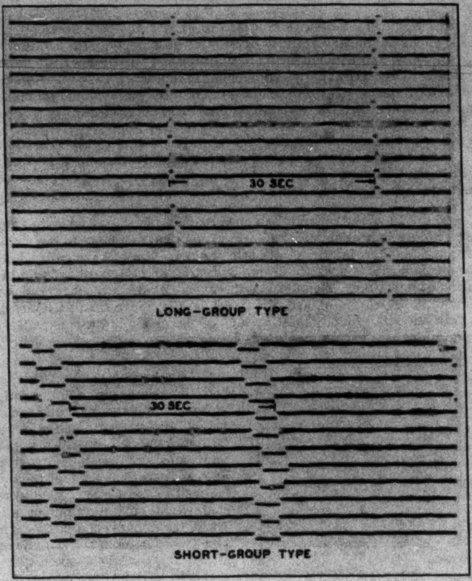

Fig. 1--Wood-Anderson recordings of short-period microseisms at Florissant

Table 1--Short-period microseismic activity monthly and seasonal distribution

Period	Pct active	Period	Pct active
January	20	July	25
February	19	August	25
March	33	September	22
April	34	October	19
May	45	November	29
June	27	December	21
Spring	37	Autumn	23
Summer	26	Winter	20
	Total 27		

the spring and a decrease to a minimum of 20 pct in the winter months. If a sufficiently large sample was obtained, this distribution is in sharp contrast to the seasonal distribution of four- to eight-sec microseisms, which are most active in the winter.

Arbitrarily chosen storms

These short-period microseisms are confined to rather discrete sections of the Wood-Anderson seismograms. These periods of activity or storms commence with a rather steady increase to maximum displacements and concentration of activity and finally return either gradually or abruptly to quiescence. Very arbitrarily, some 155 storms from 1948-1951 were selected for detailed study as described above. The only guide to selection was that the storms presented displacements larger than ordinary background (one mm or greater) that they were clearly recorded.

Periods--Probably the most noticeable fact from these data is the great preponderance of 0.3-sec periods. In only eight cases were 0.4-sec period waves recorded. The constancy of recorded period within the individual groups and trains throughout the storms is one of the most characteristic and perhaps significant features of these microseismic disturbances.

Storm duration--Unlike many other types of microseisms, these short-period microseisms near St. Louis vary widely in storm duration, from less than one hour to over 40 hours. By far, the majority, however, are found to last from six to 24 hours. While it appears impossible to characterize a particular season with a specific storm duration, some importance must be attached to seasonal distribution of durations. Notable are the great majority of occurrences of storms lasting less than one hour in the summer, and of storms lasting more than 24 hours in the transitional seasons of spring and autumn. Also a relative lack of the shortest storms is to be found in autumn and winter and of the longest storms in winter.

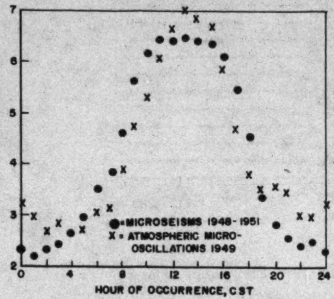

Fig. 2--Hourly occurences of microseisms and atmospheric micro-oscillations

Occurrence times--Figure 2 represents the hourly occurrences (number of times the microseisms are noted at each hour of the day) for the 155 arbitrarily selected microseismic storms. Ordinate values are given in percentages of the total number of such observations. First, it may be remarked that none of these values can be considered insignificant. Also a significant number of these storms start during all days of the week. Thus, the occurrence of these microseisms in significant numbers at all hours of the day and on all days of the week, taken with the usual quietness of the Florissant surroundings, strongly suggests that traffic and industrial disturbances are not the primary sources as has been suggested by OMORI [1908], GUTENBERG [1932], LYNCH [1938], and CARDER and GILMORE [1945] for recorded disturbances of this order of period.

The pronounced increase in microseismic activity between about 08h 00m and 19h 00m CST (Fig. 2), as well as the duration of these storms, suggested a possible relationship with short-period microbarographic oscillations, especially after the findings of CLARK [1950]. Figure 2 also shows the hourly occurrences of some 259 microbarographic storms recorded by the Macelwane microbarographs at Florissant during 1949. The obviously increased activity of both the short-period microseisms and atmospheric micro-oscillations between 08h 00m and 19h 00m CST is striking. In both cases, the maximum number of occurrences appears at 13h 00m CST.

Figures 3, 4, and 5 show the occurrence histograms of the beginning and ending times of the microseismic and microbarographic storms and of the times of maximum microseismic displacements, respectively. These times are plotted at the nearest hours. The general similarities between the two phenomena with regard to the beginning and ending times of the storms are displayed by the figures. In his study of atmospheric micro-oscillations at Florissant, CLARK [1950] determined that the larger amplitudes occurred more frequently between 07h 00m and 18h 00m. For these short-period microseisms, this same interval encloses more than 87 pct of the observed times of maximum microseismic displacements. The similarities in these occurrence times strongly indicates a relationship between the short period microseisms and atmospheric micro-oscillations.

This possible relationship was checked by a study of as many individual cases as possible. For only 50 of the 155 microseismic storms were the microbarographic records sufficiently clear and obtained with known calibration to permit this analysis. The average microbarographic activities

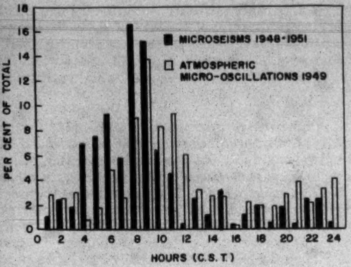

Fig. 3--Beginning times of microseisms and atmospheric micro-oscillations

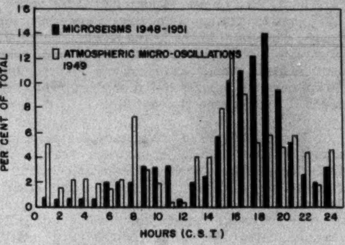

Fig. 4--Ending times of microseisms and atmospheric micro-oscillations

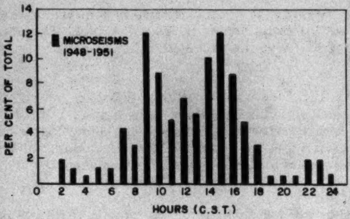

Fig. 5--Times of maximum displacements, microseisms, 1948-1951

for these 50 cases were determined by a method suggested by Clark in 1953. (The Macelwane microbarographs were originally adjusted so that a sudden injection of one cc of air produced a record displacement of one cm. With this sensitivity the following scales apply: N (none) for microbarisms having an average record amplitude less than one mm, VL (very light) average amplitude of one mm, L (light) average amplitude from one to five mm, LM (light moderate) average amplitude from five to ten mm, M (moderate) average amplitude from ten to 15 mm, and S (strong) average amplitude in excess of 15 mm. Later the sensitivity was lowered so that an injection of three cc air produced a record displacement of one cm. For this sensitivity, the following intensity scales were used: A less than one mm amplitude; B, one mm, C, 1 to 5 mm; D, 5 to 10 mm; E, 10 to 15 mm; and F, in excess of 15 mm.)

In every case available for study, the times of the microseismic storms were obviously related to increased microbarographic activity [WALSH, 1952]. The reverse relationship was also investigated. In over 100 microbarographic storms arbitrarily selected from the 1949 data, the short-period microseisms even though small in amplitude could be predicted from the occurrence of atmospheric micro-oscillations. Thus there seems to be a correlation in time between the short-period microseisms recorded at Florissant and a particular meteorological phenomenon-namely atmospheric pressure micro-oscillations recorded at the same station.

Meteorological study--Investigation of the six hour surface synoptic maps at the times of the 155 microseismic storms at once reveals that the short period microseisms appears quite unrelated to meteorological phenomenan occurring at distances of 400 mi or more from the recording station.

The one synoptic situation which is best related to the microseismic storms is that of the approach or passage of a cold frontal type discontinuity or both near Florissant. Thus, 62 storms or about 40 pct of the total 155 appear to be well associated with the approach or passage of a surface cold front or both, a cold front aloft, a squall line, or a trough. This association is in good agreement with the findings of ROSCHKE [1952] for short period micro-oscillations, with which these microseisms are correlated, in that a cold frontal passage '.....is characterized by a significantly large percentage of the (atmospheric) micro-oscillations of maximum amplitude and a rather small percentage of the total quietude' [ROSCHKE, 1952, p. 215].

The reverse relationship between cold-frontal type discontinuities and the microseisms also seems valid. In 32 cases, mostly in 1952, the approach or passage at Florissant of a cold front or both, or squall line successfully predicted the microseisms.

Although many of the remaining 93 storms occurred while Florissant was situated on the edge of a high, the synoptic situation in these cases seems of secondary importance. CLARK [1950, 1953] has found a good correspondence between microbarographic activity and atmospheric turbulence, especially in the lower levels. These 93 cases were therefore studied for signs indicative of nonfrontal convective activity. Fog, mist, smoke, and haze were taken as signs of stability, while cumulus type clouds, rainshowers, and thunderstorms were assumed as proof of convection. From only the reports listed on the six-hour maps, 57 pct of the storms showed rather positive signs of local convective activity.

The limitations of the meteorological information must be remembered. CLARK [1953] utilized hourly weather data in his analysis, yet was still obliged to interpolate somewhat in space and time. Under these limitations, it does not seem entirely unreasonable to assume local convection occurring on such a scale or perhaps at such a location as to pass undetected by analyses of this weather data and yet show its effects on the seismograph and microbarograph. The operation of the microseismic tripartite system and of the continually registering wind velocity recorders and other specialized meteorological equipment being installed at Florissant may provide the precise and continuous information essential to the determination of the exact origin of these short period microseisms. Undoubtedly, the time correlation between increased microseismic and microbarographic activities at the same station found valid in all of the 174 cases examined, should prove significant in later precise studies.

Case histories

Non-frontal convection, August 28, 1948--During this storm, an extensive barometric high of about 1023 mb covered most of the east and mid-west with its center in West Virginia. The low (1017 mb) in the Dakotas with a cold front extending into Wyoming seemed of little significance for these microseisms.

Small microseisms began about 03h 44m CST. Light fog was reported at 06h 30m, which however was dissipated by 12h 30m, with the formation of cumulus congestus. The map of 18h 30m showed cumulus congestus with a thunderstorm which apparently began about 14h 30m. Significantly, the maximum microseismic displacement occurred at 15h 47m, shortly after the beginning of the thunderstorm. Microseisms ended at 1924. No low clouds or further weather were reported at 18h 30m.

Also significant was the fact that the microseisms ended during the time when a 1020-mb high moved NW from the Missouri-Arkansas-Tennessee region (18h 30m on Aug. 28) into Central Missouri (00h 30m on Aug. 29).

This storm was one of the very few which occurred at a time when a hurricane was shown on the maps.. However, during the time of the storm (12h 30m and 18h 30m maps) this hurricane was situated more than 800 miles off the east coast of Florida, and did not move closer to St. Louis until much later.

Cold front, May 2, 1948--Between 18h 30m on May 1 and 00h 30m on May 2 a warm front passed through St. Louis. At 06h 30m on May 2 a 999-mb low was shown directly over St. Louis. Neither of these periods was marked by significant microseisms.

The microseismic storm, beginning at 08h 15m on May 2, may be attributed to the action of the cold front which moved from about 50 mi W of St. Louis at 06h 30m on May 2 to a position some 100 mi ESE at 12h 30m. Microseismic activity ended at 18h 08m, with the cold front 230 mi SE (18h 30m). Also, between 12h 30m and 18h 30m, the horizontal pressure gradient through St. Louis became considerably weaker.

Cold front aloft, March 18-19, 1950--The approach of this cold front aloft seems to have been signaled by the onset of the microseismic storm and of increased microbarographic oscillations during the latter part of hour 21 (Fig. 6). The horizontal dashes represent atmospheric micro-oscillation intensity, using the ABC scale described under 'Occurrence times.' Circles represent microseismic intensity, scale at the right. The barbed vertical strokes denote the beginning and ending of the microseismic storm and the unbarbed stroke denotes the time of maximum microseismic amplitude. The values were rather constantly high: 0.6 mm for the microseisms and C for the micro-oscillations as the frontal surface approached to 80 mi SW at 00h 30m on March 19.

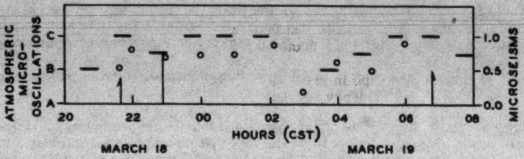

Fig. 6--Comparison of north-south microseisms component and the atmospheric micro-oscillations on March 18-19, 1950

A very sudden drop in activity was experienced by both phenomena during hour 2 of March 19, the microseisms diminishing almost to the background and the micro-oscillations to A-B. Both increased later and attained their peak values during the 6th hour. The synoptic maps indicated a passage of the cold front aloft between 00h 30m and 06h 30m on March 19; at the latter time it was shown some 190 mi E of St. Louis. Microseisms returned to background at 06h 48m on March 19. Both microseismic and microbarographic activities seemed to follow the sequence outlined by ROSCHKE [1950] for short-period micro-oscillations during a cold frontal passage.

The movements of a low during and after this storm are of great importance. During the time of the activities, this low was at all times more than 200 mi south and west of St. Louis. After the end of the storm, it advanced generally eastward and passed just to the south of St. Louis. By 06h 30m on March 20 its center was situated about 60 mi SSE of St. Louis; indeed St. Louis was within the first closed isobar (1011 mb). Its associated frontal system did not pass St. Louis. No significant microseisms were observed during this later period.

Table 2--Distance relationships microseisms and cold fronts

Beginning times before passage		Ending times after passage	
Storm	Distance	Storm	Distance
	mi		mi
4	92	4	330
10	165	5	200
18	near	8	190
22	32	9	240
24	40	18	230
54	11	24	50
57	150	34	200
61	100	54	40
85	45	64	360
88	190	78	230
89	near	90	150
110	near	99	200
116	45	103	200
118	near	111	190
119	75	141	75
124	60	144	75
132	near	146	150
145	250	148	110
148	150		

Distance relationship--It appears that the duration of a microseismic storm associated with a cold frontal type discontinuity may depend upon the speed and vigor of the front, as well as the ensuing synoptic pattern. The approach of a high, which often follows a cold front, near Florissant seems quite effective in damping the microseisms.

The distance over which a cold front is effective in generating these microseisms depends on whether the recording station is in the pre- or post-frontal interval. Table 2 lists the interpolated distance to St. Louis for storms beginning before the passage and for storms ending after the passage. These figures would seem to indicate that conditions suitable for the generation of these short-period microseisms exist after the frontal passage more vigorously than before the passage.

The usefulness of the seismograph in prediciting the character of front passages must await more detailed proof, though some evidence seems to favor this possibility.

Distinguishing characteristics--One of the major difficulties in predicting cold-front approaches from these microseismic storms seems to be the fact that no unique characteristic is evident in the records to distinguish storms associated with cold fronts from those of non-frontal convection origin. For the Florissant station, an attempt has been made in this direction on the basis of seasonal distribution of occurrences of storm duration, times of beginning, ending, and maximum microseismic displacements, and character of the recorded group type.

In this regard, it seems quite interesting that all seasons except winter show a pronounced concentration of non-frontal microseismic storms under the short-group type and that summer is the only season whose cold-front storms are markedly of the short-group type. This last, with the fact that few winter cold front storms are of pure short-group type, would seem to be indicative of a fundamental difference in behavior or structure between summer and winter cold fronts.

Meteorological conclusions--Many of the findings from this study seem in agreement with the conclusions of ROSCHKE [1952] for microbarographic oscillations and of DONN [1950] for microseisms of about 1.5-sec period associated with cold fronts over water areas.

(1) The 0.3 sec microseisms at Florissant are apparently unrelated to synoptic features 400 mi or more from the station.

(2) Warm fronts and barometric highs and lows near the stations are ordinarily not effective in generating this period band. Indeed, the presence of a nearby high seemingly hinders the production or dampens the activity of these microseisms.

(3) The approach or passage or both at Florissant of a cold frontal-type discontinuity seems related in time to the recording of these short period microseisms. In general accord with ROSCHKE [1952] findings for micro-oscillations, these microseisms often make their appearance and may even reach a peak of activity somewhat in advance of the passage, decrease in activity at or just before passage, and again increase to major activity usually of an extended duration in the post-frontal interval.

(4) Under the limitations of the meteorological information applied, there appears some relationship between increase of microseismic activity and increased surface wind speed and a tight horizontal pressure gradient.

(5) In many non-frontal cases, some evidence may be found in the six-hour maps for relating these microseisms with convective activity near the recording station, the peak microseimic displacement often occurring with the more pronounced convective weather elements. Similar results have been found by CLARK [1950, 1953] for short period atmospheric micro-oscillations.

Since these short-period microseisms are apparently recorded quite often by instruments of such divergent construction and instrumental constants as short period Benioffs, Wood-Andersons, Sprengnethers, and instruments of individual design at many widely scattered stations, it appears that these recorded oscillations are not due to mere instrumental difficulties. Considerations of the relative insensivity of the Macelwane microbarograph to seismic disturbances [HEINRICH, 1950] and the dissimilarities in period, waveform, and group form between the ordinarily recorded microseisms and atmospheric micro-oscillations indicate that these disturbances, correlated in time, are not atmospheric micro-oscillations recorded on seismographs or microseisms recorded on microbarographs. This then seems to be a time correlation between true ground oscillations and true atmospheric oscillations recorded at the same place.

Nature--Little can be said at present of the nature of these microseisms. The constancy of their period is a feature which is quite suggestive. The establishment of their surface-wave character, or indeed their traveling-wave character, is a matter best resolved by the matched, high magnification instruments of the tripartite arrangement [MACELWANE, 1948]. Possibly, solution of this problem may be found in a phenomenon similar to those suggested by SEZAWA and KANAI [1939], by HASKELL [1951], or by JARDETZKY and PRESS [1951].

Conclusion--Data in the form of gross hourly occurrences, times of storm beginning and ending and of maximum displacements as well as investigations of many individual cases point toward a correlation in time between small regular group microseisms of characteristics 0.3-sec period at

Florissant and short-period microbarographic activity at the same station. In accord with the findings of CLARK [1950, 1953] and ROSCHKE [1952] for atmospheric micro-oscillations, the great majority of these microseismic storms seem associated either with the approach or passage or both at the station of a cold frontal-type discontinuity or with local, non-frontal convective activity. Atmospheric turbulence seems a prime factor in the generation of these microseisms. A study of hourly activities of the correlated microseisms and micro-oscillations suggests that while these oscillations are probably not related as cause and effect they may well proceed from the same source. Finally, this study suggests that with more precise knowledge of the method of production and propagation of these oscillations, combined analyses of these short period microseisms and micro-oscillations may prove useful tools in elucidating the local turbulence mechanism of the atmosphere.

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A NOTE ON THE MANNING FORMULA

Ven Te Chow

The classic Manning formula is one of the foundation stones of the modern open-channel hydraulics. Owing to its simplicity in form and satisfactory results it lends to practical applications, this formula becomes the most widely used one of all other formulas for open channel computations. This is true particularly in the United States. Despite its popularity, however, the fact is often ignored that the present appearance of the formula is not in the form which the distinguished Irish engineer [MANNING, 1891] first proposed in a paper which was read on December 4, 1889 at a meeting of the Institution of Civil Engineers of Ireland. A summary of the derivation and background of various velocity formulas, including Manning's is given in Calculation of Flow in Open Channels, Tech. Rep. pt. 4, Miami Conservancy District, 1916. (Ed.) As first published, the formula took the form

$$V = C\sqrt{Sg}\,[R^{0.5} + (0.22/m^{0.5})\,(R - 0.15)]$$

in which V represents the mean velocity in seconds, for all measures of length; C, a coefficient which varies with the nature of the channel bed; S, the sine of the angle of inclination of the water surface; R, the hydraulic radius; g, the gravitational acceleration; and m, the height of the barometric column. Comparison of this formula with seven other formulas was made for actual observation. Finally, based on BAZIN's [1865] data and applications to 170 experiments, a simple form was established as follows:

$$V = CS^{1/2}\,R^{2/3}$$

Manning, however, mentioned that this simple form was also previously developed independently by Hagen. He acknowledged this credit to Hagen by quoting a statement by Cunningham [1882].

The Manning formula was later modified and expressed in metric units as

$$V = (1/n)\,R^{2/3}\,S^{1/2}$$

where n is the coefficient of roughness, and V is in meters per second and R in meters. Since one meter = 3.2808 ft, the formula in English units obtains its coefficient as $(3.2808)^{1/3} = 1.4858$. The Manning formula presented in most hydraulics textbooks nowadays appears in the form

$$V = (1.486/n)\,R^{2/3}\,S^{1/2}$$

Considering the approximations involved in the derivation of this formula and the uncertainty of the value of n, it seems to be not justifiable to carry the numerical coefficient, 1.486, to more than three significant figures. It is suggested that a value equal to 1.49 is sufficiently accurate for its practical purpose. It is noted that several very recent publications have justified the form and adopted this suggested value.

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COMPARISON BETWEEN STANDARD AND SMALL ORIFICE RAINGAGES

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Introduction--The standard gage used for precipitation measurements by the U. S. Weather Bureau has a catch diameter of eight inches. In the past several years numerous small orifice gages have appeared on the market. These are much cheaper than the standard gage, and installation and maintenance are simple. Therefore, it would be advantageous to use them where recording gages are not required and where exceptionally large capacity is not needed, if their collection efficiency approaches that of the standard eight-inch gage. Dense networks desirable for various hydrological and agricultural research projects could be installed where cost of standard gage networks are presently prohibitive for this purpose.

During 1953-54, an observational program was carried out in Illinois to compare the rainfall catch obtained from several sizes of non-recording gages. Under this program, the catch of four small orifice gages was compared with that from the U. S. Weather Bureau standard eight-inch stick gage to obtain relations between the gages with varying storm size and wind speed.

The investigation was undertaken to supplement existing information on the effect of gage size in rainfall sampling and to evaluate currently popular types of small orifice gages. Several investigators have previously studied the effects of gage size on precipitation catch. Among these are CONOVER and NASTOS [1951] who tested three-inch and 0.75-inch gages, and DENISON [1941] who compared the Canadian 3.75-inch and U. S. Weather Bureau eight-inch gages. These investigators obtained results favorable to the use of small gages. A similar conclusion was reached by PURI [1931]. Other discussions on the subject have been presented by KLEINSCHMIDT [1935, pp. 275-288] and by MIDDLETON and SPILHAUS [1953, pp. 120-121].

Description of gages--A brief description of the gages used in the comparative study is given in the following paragraphs. Scaled drawings of each gage are shown in Figure 1.

The standard eight-inch stick gage of the U. S. Weather Bureau was employed as a comparison standard for evaluating the small orifice gages. The Weather Bureau gage consists of an outer cylinder having an eight-inch diameter which is connected to a smaller inner cylinder by means of a funnel. The inner cylinder has a cross-sectional area one-tenth that of the outer cylinder (catch area). Measurements are made with a stick graduated in inches and tenths, corresponding to tenths and hundredths of an inch of rain, which is inserted into the inner cylinder through the hole at the apex of the funnel. Height of the gage is 26 inches. The gage is supported by a tripod, giving an overall height of about 33 inches for the entire assembly. Capacity is 24 inches.

The three-inch gage is essentially a small scale model of the Weather Bureau eight-inch gage. The catch diameter of the outer cylinder is three inches. Like the Weather Bureau gage, the inner cylinder has a cross-sectional area one-tenth that of the outer cylinder catch area and measurement is made by means of a graduated stick plunged through the funnel. Total height of the gage is 13.5 inches and capacity is 12 inches.

The plastic wedge-shaped gage has a wedge-shaped well on which a measuring scale is imprinted. The rectangular catch area is 2.5 inches by 2.3 inches. The gage has a capacity of six inches and has a metal bracket for mounting on a post. The scale is graduated in hundredths of an inch to a depth of two-tenths of an inch, then in 0.02-inch intervals to one inch, and in 0.05-inch intervals above one inch. This change in graduation is due to the wedge shape, a feature which provides excellent reading accuracy with light to moderate rainfall amounts. Total height of this gage is 13.5 inches.

The 1.15-inch tube gage consists of a cylindrical plastic tube having a 2/3-inch inside diameter, and containing an aluminum funnel which provides a 1.15-inch diameter catch area. Proportion of the gage parts is such as to give a catch magnification of 1 to 3. The tube is mounted on an aluminum frame, suitable for mounting on a post. A scale graduated in tenths of an inch is debossed in the metal frame. Overall height of the assembly is about 19 inches and gage capacity is six inches.

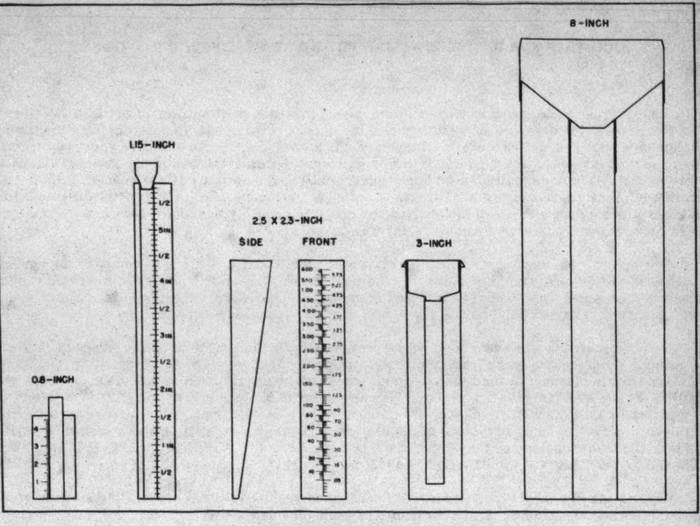

Fig. 1--Gages used in comparison study

The 0.8-inch tube gage is the familiar farm fence post type, frequently given away under advertising campaigns by seed and feed companies. The two gages used in this study consisted of a glass tube having an 0.8-inch inside diameter mounted on a metal frame provided with a painted graduated scale. No magnification of catch is provided with these gages which have a capacity of six inches.

Data used in analysis--Two sets of small orifice gages were operated in conjunction with two standard eight-inch gages from March to November, 1953-54. Consequently, most of the data were from shower-type storms. The four small gages in each set were installed at distances of six feet from a standard eight-inch gage to form a circular pattern (Fig. 2, Stations B, D). Readings were made as soon as possible after the end of each storm to minimize evaporation effects. The calibration of each gage was checked before installation. The level of each gage was checked periodically and the gages kept as free of dirt, insects and other foreign material as possible. All except the three-inch gage were installed on small posts at the level of the eight-inch gage. Since it had no provisions for post mounting, the three-inch gage was installed on the ground surface as recommended by the manufacturer.

Both gage sets were installed at the University of Illinois Airport on level meadow land in the middle of a micro-network of eight-inch stick gages, consisting of nine pairs of gages at six-ft intervals located 300-ft apart on a rectangular grid pattern (Fig. 2). Thus, a record of the variability observed between pairs of standard gages six feet apart was available for comparison with the variability obtained between the small and standard gages. Three pairs of 8-inch gages spaced six feet apart were used for comparison with the two small gage-standard gage sets (Fig. 2., Stations A, C, E).

Analysis of data--Analysis of collected data was first made separately for each set of gages. However, significant differences did not appear to exist between the sets so they were combined in

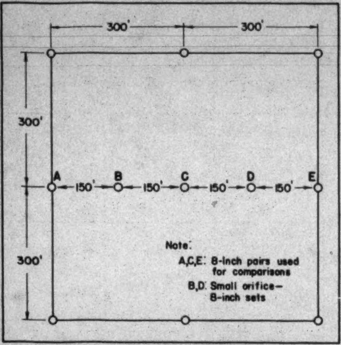
300'
300'
300'
300'
A
B
C
D
E
150'
150'
150'
150'
Note:
A,C,E: 8-inch pairs used for comparisons
B,D: Small orifice-8-inch sets

Fig. 2--Location of comparison gage sets within micro-network

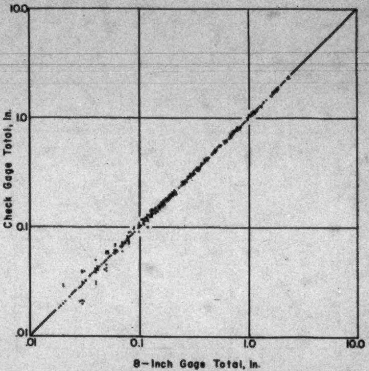

Fig. 3--Comparison between eight-inch gages, six feet apart

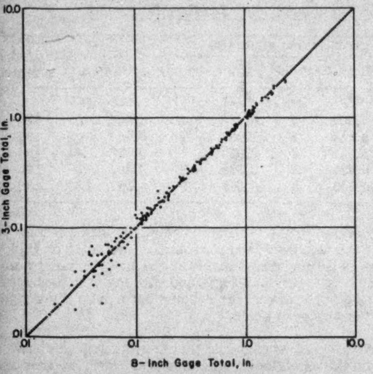

Fig. 4--Comparison between eight-inch and wedge shape gages

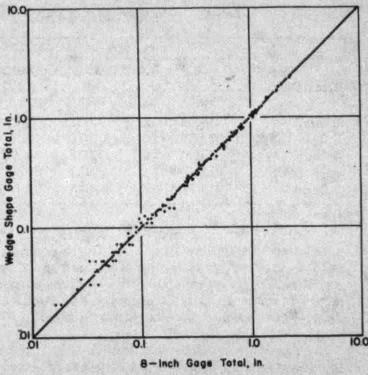

Fig. 5--Comparison between eight-inch and three-inch gages

the final analysis to provide a larger sample for statistical comparisons. Scatter diagrams comparing the various small gages and the standard eight-inch gages are shown in Figures 3-7. Examination of these graphs indicates that the wedge-shaped and three-inch gages compared best with the standard eight-inch gage. This is further borne out by the summary in Table 1. In this table, the average deviation from the eight-inch gage reading for each small orifice gage has been calculated for various storm sizes. A similar calculation between the three six-foot pairs of eight-inch gages has been included for comparative purposes. The average deviation has been expressed in both inches and per cent. Results presented in the table indicate that the wedge-shaped and three-inch gage compare most favorably with the eight-inch gage, followed by the 1.15-inch gage and the 0.8-inch gage. As might be expected, the smallest deviations were obtained between the pairs of eight-inch gages.

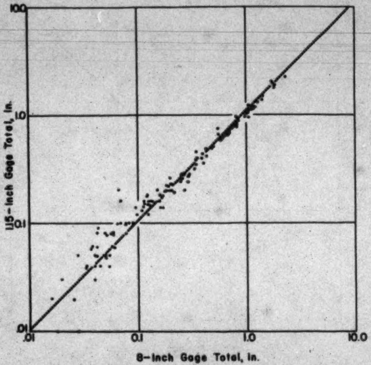

Fig. 6--Comparison between eight-inch and 1.15-inch gages

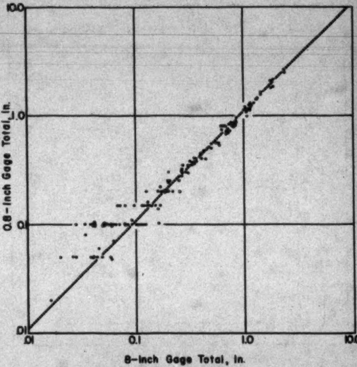

Fig. 7--Comparison between eight-inch and 0.8-inch gages

Table 1--Comparison of catch between standard and small orifice gages

Gage	Average deviations for given storm sizes (in)								All storms		Number of samples
	0.01" - 0.19"		0.20" - 0.49"		0.50" - 0.99"		1.00" - 2.00"				
	inch	pct	inch	pct	inch	pct	inch	pct	inch	pct	
8-inch	0.003	4	0.005	2	0.007	1	0.018	1	0.006	2	281
2.5-in × 2.3-in	0.008	10	0.016	5	0.023	3	0.030	2	0.017	4	112
3-inch	0.010	12	0.013	4	0.018	3	0.057	4	0.020	4	154
1.15-inch	0.020	23	0.027	9	0.035	5	0.069	5	0.032	7	125
0.8-inch	0.032	37	0.037	12	0.056	8	0.124	9	0.052	12	140

Some of the comparatively large scatter exhibited by the 0.8-inch gage in Figures 3-7 may be attributed to the difficulty in reading amounts to the nearest 1/100 of an inch. The scale on this gage is marked off in tenths of an inch and there is no magnification of the catch. The same reading difficulty to a lesser degree was observed with the 1.15-inch gage, and with the wedge-shaped gage for amounts above one inch. For small amounts, however, the reading error with the wedge-shaped gage should have been negligible due to the expanded scale.

Examination of the data indicated that the wedge-shaped gage and the three-inch gage caught the same amount of rainfall on the average as did the eight-inch gage. However, the 1.15-inch and the 0.8-inch gage showed a tendency to catch more rainfall than did the standard gage. This was particularly true with the 0.8-inch gage, and the tendency was greatest with the light rainstorms.

Although exceptional care was taken in emptying the gages after each rain, it was thought that water draining back from the sides after emptying might be an appreciable factor in the tendency for the 1.15-inch and 0.8-inch gages to read high. To check this possibility, the data were reanalyzed, omitting all observations occurring within one day of a previous rain. Result of this analysis was reduction of the median catch ratio between each small gage and the 8-inch gage from 1.10 to 1.08 for the 0.8-inch gage and from 1.04 to 1.03 for the 1.15-inch gage.

To investigate further the tendency of the 1.15-inch and 0.8-inch gages to catch more rainfall than the standard gage additional analysis which is summarized in Table 2 was made. Storms were classified both by storm size and wind speed, and median ratios between the small gages and the standard gage were computed for the various classifications. Limitations of the data prevented more detailed classification of wind speeds. The storm size classification is based upon observations at the standard gage. Winds speeds are averages for the rainfall period observed with an Aerovane wind system located about 0.5 of a mile from the gages.

Reference to Table 2 shows a general tendency among the small gages to give higher ratios at low rainfall amounts, especially at higher wind speeds (11-20 mph). For a given storm size, a general tendency for the ratio to increase with wind speed was observed for the light storms (0.01" - 0.49"). Similarly, a tendency for the ratio to decrease slightly with increasing wind speed in heavy rainstorms (0.50"- 2.00") was noted.

Table 2--Effect of wind speed and storm size on catch of various gages

Wind speed	Median ratio for given storm sizes				All storms
	0.01" - 0.19"	0.20" - 0.49"	0.50" - 0.99"	1.00" - 2.00"	
mi/hr	2.5 inch × 2.3 inch gage to eight-inch gage				
0-10	1.00	0.98	0.99	1.02	1.00
11-20	1.00	0.99	0.98	0.99	0.99
	Three-inch gage to eight-inch gage				
0-10	1.00	1.00	1.00	1.00	1.00
11-20	1.09	1.03	1.00	0.97	1.01
	1.15-inch gage to eight-inch gage				
0-10	1.15	1.03	1.00	1.00	1.04
11-20	1.25	1.02	0.96	0.97	1.02
	0.8-inch gage to eight-inch gage				
0-10	1.30	1.09	1.05	1.08	1.13
11-20	1.25	1.11	1.05	1.05	1.10

Summary and conclusions--Results of the study indicate that the small orifice gages are satisfactory for use in place of the standard eight-inch gage for measuring rainfall under most circumstances. No tests were made of the gages during snowfall. Of the particular gages tested, the wedge-shaped and 3-inch gages gave the best comparison with the standard gage.

The suitability of the small orifice gages may be further evaluated by reference to Table 3 which has been extracted from a report under preparation by the author. The relations shown in this table were obtained from observations in shower-type rainfall collected on a 50-gage network within a 100-sq mi area. Except for light storms, the average rainfall variability in shower-type rainfall within a distance of one mile is greater than that between any of the small gages and the standard gage shown in Table 1.

Table 3--Variation of point rainfall with distance

Storm size at given point	Average difference at point one-mile away	
inch	inch	pct
0.10	0.016	16
0.25	0.033	13
0.50	0.056	11
0.75	0.075	10
1.00	0.094	9
1.50	0.130	9
2.00	0.163	8

No opinion is offered regarding the absolute catch efficiency of the various gages. Comparisons were based entirely upon compatability with the Weather Bureau gage which is the generally accepted standard for rainfall measurements in the United States.

No tests were made of the durability of the various gages. The wedge-shaped and 1.15-inch gages have plastic containers, while the 0.8-inch gage has a glass container. The manufacturers do not recommend their use in freezing weather. The three-inch metal gage does not have this shortcoming.

Before using a small orifice gage, the calibration should be carefully checked. The relatively small catch areas employed make them subject to appreciably large observational errors with small absolute errors in orifice diameter or measuring scale.

Because of their small catch volume, exceptional care should be taken to keep the small orifice gages free of dirt, insects and other foreign material. Swabbing out of the small measuring tubes after each reading will insure greater reading accuracy by eliminating water draining back from the sides and any dirt which may be present.

Acknowledgments--The writer wishes to acknowledge the assistance of Carol Verseman, Research Assistant, who performed a major portion of the observing, tabulating and anlytical work. The report was prepared under the direction of A. M. Buswell, Chief, and general guidance of G. E. Stout, Head, Meteorologic Subdivision, Illinois State Water Survey.

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REPORT OF THE SPECIAL COMMITTEE ON THE GEOPHYSICAL AND GEOLOGICAL STUDY OF CONTINENTS, 1952-1954

George P. Woollard, Chairman

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C. S. Beals
Francis Birch
Walter H. Bucher
Maurice Ewing
R. A. Geyer
Ross Gunn
A. J. Hoskinson
Patrick M. Hurley
Gordon Lill
E. B. Roberts
Howard Tatel
W. T. Thom, Jr.
W. S. White
James T. Wilson
J. Tuzo Wilson
J. Lamar Worzel

General remarks--As the Executive Committee of the A. G. U. had requested the Committee on Continents to represent the interests of the Special Committee for the study on Ocean Basins on a pro tem basis, it was felt it would be appropriate this year to summarize the work being done in both areas. This was felt to be particularly desirable as there has been no recent report covering the scope of the extensive geophysical program in the oceans and as during the coming International Geophysical Year a coordinated program of study over both the continents and ocean basins is being planned.

Seismic studies of crustal structure

Earthquake analyses--U. S. Coast and Geodetic Survey (E. B. Roberts, and L. M. Murphy): An investigation of instrumental and non-instrumental strong-motion data is being made to establish correlations between earthquake intensity, ground acceleration, ground period, and epicentral distance. Microseism analyses indicate that microseisms with a 7- to 9-sec period travel with little change across the continent in both an east and west direction, while microseisms having periods of 3 to 7 sec are strongly absorbed. The attenuation rate across the western Atlantic is about ten times that observed across eastern North America and somewhat greater than the attenuation observed across the western Cordillera. These studies appear to support the Lorguet-Higgins idea that microseisms are generated by a second order effect resulting from oppositely moving swells in the ocean. Preliminary results of the study on the role of tidal forces in triggering earthquakes completed in 1954 indicate that tidal effects are small and masked by the effect of water loading along coast lines. An additional study as to the effect of horizontal stresses along fault systems is planned. Of tectonic interest was the occurrence of an earthquake (Magnitude 7) off the south coast of Spain on March 29, 1954 with a focal depth of 600 km. In connection with the Kamchatka earthquake of November 4, 1952 (magnitude 8.5) which was followed by about 500 after shocks of intensity 5 and greater, it appears this was related to movement along the Kurile-Kamchatka Trench described by Russian sources as an ocean deep 500 km long and 5 km wide with a depth of 34,000 ft. It appears definite that the root of the Sierra Nevada intercepts the direct P normal wave from certain regional earthquakes giving time delays in the first arrival up to eight seconds. Present zones of tectonic activity in the United States as indicated by earthquakes are shown in Figure 1. This map, prepared by Woollard, is based upon data of the U. S. Coast and Geodetic Survey and other catalogues.

Columbia University, Lamont Geological Observatory (F. Press, and W. M. Ewing): Work is being continued on the study of the propagation of the Lg phase across the Arctic region as part of an investigation to differentiate continental and oceanic crustal structure. In order to obtain more information on the mantle waves from large earthquakes, a Columbia long-period seismograph has been installed at Pietermaritzburg, South Africa, and another at Perth, Western Australia. Model studies on core phases and surface waves are being continued. The study of the dispersion of surface waves over continents and oceans has been advanced considerably, as has the study of T phases with long continental paths.

Dominion Observatory, Ottawa (C. S. Beals): Through the installation of three seismograph stations (Victoria, Alberni, and Horseshoe Bay) in southern British Columbia, a study is being made (W. H. Milne) to locate accurately local earthquakes and to correlate their occurrence with struc-

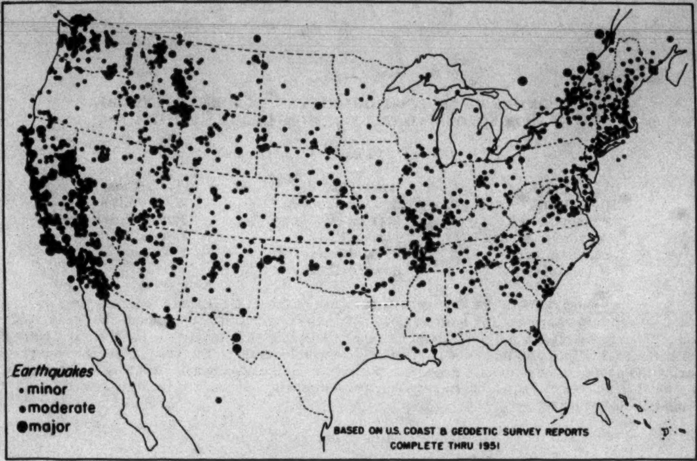


Fig. 1--Earthquake epicenters of the United States

tural trends. The study, based on rock bursts at Kirkland Lake (J. H. Hodgson), shows no layering in the crust. Observed velocities are 6.234 ± 0.012 km/sec for P_1 and 8.176 ± 0.013 km/sec for P_n. The crustal thickness found is 36 km (44 km from S_n). Possible differences in the rate of variation of P and S velocities with depth are being investigated as an explanation of late arrivals of S_n.

University of California (P. Byerly): From a study of the delays in P_n for California earthquakes recorded at Reno, Nevada, it is concluded that the root of the Sierra Nevada contains a great deal of basalt at depth.

Blast studies (continental)--Carnegie Institution of Washington, Department of Terrestrial Magnetism (M. A. Tuve, H. E. Tatel and P. Hart): An analysis of the best velocity-depth curves based on blast studies shows most of the crustal velocity increase is in the lower sixth of the crust: otherwise the data do not substantiate any particular velocity-depth distribution or layering. Present data cannot distinguish between critical reflection or refraction at the Mohorovicic discontinuity. A great deal of the observed seismogram complexity is related to conversion of compressional waves at the surface to surface waves. These converted waves observed in the field have also been found along with their converse in model studies by Tatel. Using a two-km array, Hart has found a near vertical reflection, but a change in array or shot position of only a few kilometers does not corroborate this. Conclusions based upon studies to date carried out in the Atlantic Coastal Plain and Piedmont region, the Appalachian Mountains, the Shield area of Minnesota, the Colorado Plateau, the Basin and Range Region, and the Pacific Coast Range region are: (a) most of the ground motion following a distant explosion is due to the efficient conversion of body waves to long trains of slow surface waves. These account for the so-called 'phases' observed, and on this basis of explanation for these 'phases' there is no evidence for crustal layering; (b) the seismic method has a rather limited resolution with respect to the finer points of crustal structure, and only the broader aspects may be inferred; (c) the crust is an inhomogeneous entity whose wave velocity increases only slightly with depth; (d) the overall structure of the continental crust cannot be described by either the Airy or Pratt theories of isostasy. A summary of results obtained in individual areas is given in Table 1. Figure 2 shows the locations.

Table 1--Summary on results of blast and rock-burst studies

Area	Velocity P_1	Velocity P_n	Depth of Moho. dis.	Surface elevation	Critical reflection	Observer
	km/sec	km/sec	km	ft		
Coastal Plain						
Md.-Va.	6.1	8.1	26-29[a]	100	yes	Tuve, Tatel, and others
Appalachian Mts.						
Va.-Tenn.	6.0	8.1	39[a]	2,500	yes	Tuve, Tatel, and others
Canadian Shield						
Minnesota	6.1	8.1	37[a]	1,400	yes	Tuve, Tatel, and others
Coast Ranges						
Calif. (Corona)	6.0	8.0	23-32[a]	1,500	no	Tuve, Tatel, and others
Washington	6.0	8.0	30[a]	1,200	no	Tuve, Tatel, and others
Pacific Coast						
Puget Sound	6.0	8.0	19[a]	700	no	Tuve, Tatel, and others
Calif. (Santa Cruz)	6.0	8.0	23[a]	120	no	Tuve, Tatel, and others
Colorado Plateau						
So. Boundary-North	5.8	8.1	34[a]	7,000	yes	Tuve, Tatel, and others
So. Boundary-South	5.8	8.1	28[a]	4,500	yes	Tuve, Tatel, and others
Basin and Range						
E. Boundary-East	5.5	8.0	29[a]	6,500	no	Tuve, Tatel, and others
Canadian Shield						
Adirondacks						
Central	6.43	8.1	36 ± 2	1,200	no	Katz
East	6.28	8.1		1,100	no	Katz
New England Highlands	6.13	8.4	36	200	?	Leet
Appalachians						
Penn.	6.04	8.2	33 ± 3	750	no	Katz
Pacific Coast						
British Columbia	6.39	8.17	33	0	- -	Milne
Canadian Shield					- -	
Ontario	6.23	8.18	36	1,000	- -	Hodgson
Michigan-Wis.	6.16	8.17	36.1[a]	1,460	- -	Slichter
Wisconsin	6.22	8.17	36.4[a]	640	- -	Slichter
Interior Lowlands						
Iowa-Wisconsin	6.12	8.17	37.1[a]	550	- -	Slichter
Allegheny Plateau						
New York	6.2	7.8	38	80	- -	Slichter
New England Highlands					- -	
Connecticut	6.2	7.8	25	50	- -	Slichter
Coast Range Area						
So. Calif.	6.2	8.0	32	1,500	- -	Shor

[a] On assumption of no increase in the velocity of P_1 with depth.

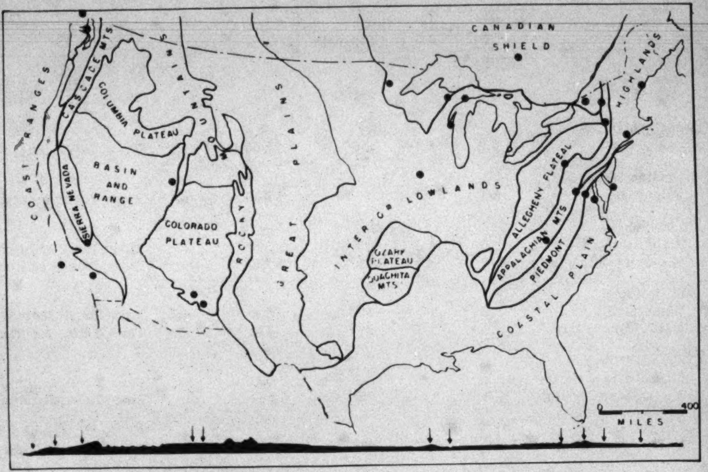


Fig. 2--Location of blast studies of crustal structure in North America

Columbia University, Lamont Geological Observatory (S. Katz): Blasts at Benson Mines and Tahawus in New York, and Milroy, Pennsylvania, have been recorded out to 309 km. The data obtained indicate an essentially homogeneous crust with a slight increase in velocity values with depth. The average crustal thickness is 34.6 km with no significant difference between areas. No near vertical reflections from the Mohorovicic discontinuity were observed. In New York P_1 = 6.39 and 6.31 km/sec; in Pennsylvania P_1 = 6.04 km/sec; P_n = 8.14 km/sec.

California Institute of Technology (G. Shor, Jr.): Reflections from the Mohorovicic discontinuity at normal and post-critical incidence have been obtained from quarry blasts at Monolith and Corona, California. The discontinuity is 32 km below sea level. A normal incidence reflection from a depth of 26 km was also obtained at Monolith. P_1 = 6.2 km/sec. The refraction data obtained support the idea of a low velocity zone at depth.

Dominion Observatory, Ottawa (W. G. Milne, and P. K. Wilmore): The observations at Victoria, Alberni, and Horseshoe Bay, British Columbia have been used to record blasts off the West Coast. Preliminary results give a depth of 33 km to the Mohorovicic discontinuity with a value of P_1 = 6.39 km/sec and P_n = 8.17 km/sec. A 12-station apparatus with seismometer stations up to 5 miles apart and with results centrally recorded via radio has been developed for blast and local earthquake studies.

Blast measurements (marine)--M. Ewing, R. Raitt, J. B. Hersey, C. Officer, and T. F. Gaskell): Results of seismic measurements at sea concerning crustal structure show that in general there is a relatively thin veneer of sediments, 0.5 to 1.5 km thick, which is underlain by rock having a velocity of approximately 6.4 km/sec, which averages between three to six km in thickness. Immediately beneath this at a depth of from 10 to 12 kms below sea level, the Mohorovicic discontinuity is encountered. Exceptions to this generalization have been noted in connection with oceanic islands (Bermuda, Bikini, Kwajalein, Funafuti, and Nukufetau), submerged guyots, the continental border area and areas on the landward side of the Andesite Line. In the case of oceanic islands one or more layers having velocity values in the range 3 to 5.5 km/sec are observed above the 6.4 km/sec layer with evidence of downwarping of both this layer and the Mohorovicic discontinuity. On the landward side of the Andesite Line in the Pacific Ocean, three layer structure is reported with the layer above the Mohorovicic discontinuity having a velocity somewhat less than

6.3 km/sec. On the Atlantic continental border of North America the Mohorovicic discontinuity has been observed to be at about 17 km and overlain by two layers beneath the sediments having velocities of 4.9 km/sec and 6.75 km/sec respectively. Table 2 summarizes data for the marine areas.

Table 2--Marine seismic data from blast studies

Area	P_1	Depth	P_2	Depth	P_n	Depth of M.D[a]	Depth of water	Observer
	km/sec	km	km/sec	km	km/sec			
N. W. Atlantic	- -	- -	6.42	6.2	7.97	12.0	5.20	Ewing and others
Nares Basin	4.5	5.4	6.53	6.7	8.5	11.1	5.34	Officer and Ewing
W. No. Atlantic	- -	- -	7.2	6.0	8.3	9.5	4.8	Ewing and others
Bermuda Flank	4.49	5.1	6.67	9.9	?	?	4.43	Officer and Ewing
Gulf of Mexico	3.2	6.0	6.2	10.7	8.3	17.5	3.7	Ewing and others
Caribbean	- -	- -	5.94	5.5	7.81	13.5	21.0	Ewing and others
Bronson Deep	4.3	5.7	6.64	7.9	7.94	10.4	5.30	Hersey and Officer
Continental Slope	4.9	6.0	6.75	8.05	8.48	15.9	2.77	Officer and Ewing
Gulf of Maine	5.3	0.02	6.24	5.2	7.5	16.5	0.02	Katz
East Pacific	- -	- -	6.75	6.1	8.1	12.0	5.5	Raitt
Bikini Flank	5.1	6.3	6.53	7.2	8.2	13.0	4.6	Raitt
Central Pacific	- -	- -	6.75	7.0	8.1	10.8	5.5	Raitt
English Channel	5.5	2.0	?	?	?	?	0.01	Hill
N. E. Atlantic	- -	- -	6.6	5.9	?	?	4.7	Hill
Hawaiian Swell	4.3	0.2	6.3	2.9	?	?	0.2	Gaskell and Swallow
Hawaiian Swell Flank	- -	- -	6.3	5.0	- -	- -	4.5	Gaskell and Swallow
North Pacific	- -	- -	6.4	5.5	?	?	5.0	Gaskell and Swallow
Mariannas Area	- -	- -	6.0	6.4	8.0	9.4	4.9	Gaskell and Swallow
S. W. Pacific	- -	- -	6.4	5.9	?	?	5.5	Gaskell and Swallow
Funafuti Flank	4.0	5.4	6.3	6.9	?	?	4.9	Gaskell and Swallow
Indian Ocean	4.6	6.5	6.4	7.9	?	?	4.7	Gaskell and Swallow
Mediterranean	4.4	3.9	?	?	?	?	3.5	Gaskell and Swallow

[a] M. D. is the Mohorovicic discontinuity.

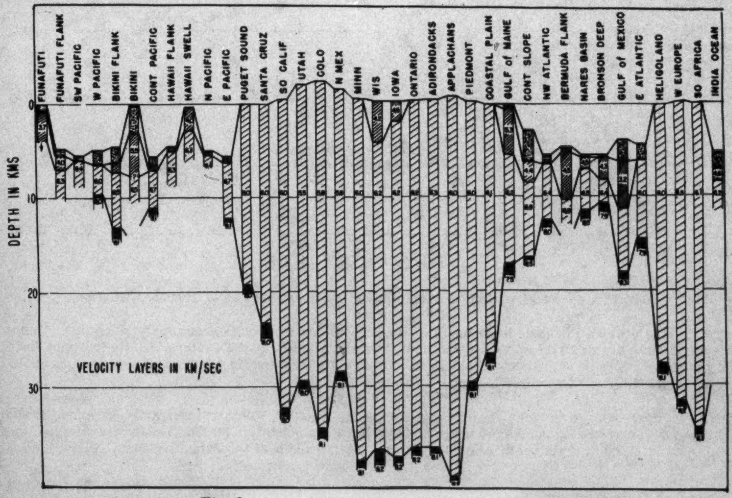


Fig. 3--Crustal structure as revealed by blast studies

Figure 3 is a graphical representation of crustal structure as revealed by both the continental and marine seismic blast studies. A first impression is that crustal structure conforms closely to the Airy theory of isostasy, but as indicated in Figure 4 in which the depth of the Mohorovicic discontinuity as revealed by blast studies is plotted as a function of elevation, the relationship is not a simple one or consistent for either the continental or oceanic areas. The groups in the United States who have been active in making seismic measurements at sea and the areas in which they have been operating are as follows:

Lamont Geological Observatory of Columbia University (M. Ewing and Others): cooperating with Woods Hole Oceanographic Institution: Crustal studies in the western North Atlantic, Caribbean Sea, Gulf of Mexico, Puerto Rico Trench, with a few measurements in the eastern Atlantic and a traverse across the South Atlantic. Studies of the geology of the continental margins particularly north of Cape Hatteras.

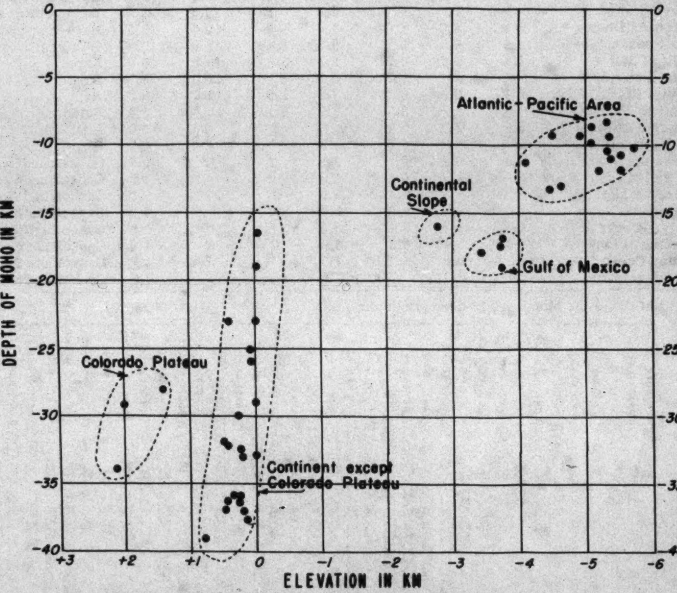


Fig. 4--Depth of Mohorovicic discontinuity as function of surface elevation

The Marine Physical Laboratory of the Scripps Institute of Oceanography (R. Raitt): Operations have been mostly in connection with crustal structure in the eastern Pacific between San Diego and Hawaii with special studies of atolls (Bikini, Kwajalein, etc.) guyots, and the Acapulco trench off the west coast of Mexico.

Department of Geology, University of Wisconsin (G. P. Woollard, and R. P. Meyer): Offshore operations are being conducted south of Cape Hatteras out to the 20-fm line as a supplement to a seismic study of the structural geology of the southern half of the Atlantic Coastal Plain.

Other seismic work--Other groups known to be conducting seismic measurements in connection with geologic studies are Princeton University, the Indiana University, the Colorado School of Mines, St. Louis University, Michigan School of Mines and Technology, Syracuse University, the University of Minnesota, Weston University, the U. S. Geological Survey and the Illinois Geological Survey. Most of the above investigations are refraction studies, but some reflection work is being done using the new high resolution reflection equipment introduced this past year. At Pennsylvania State College (B. F. Howell, Jr.), studies on the generation of seismic waves and their modification in the first few tens of feet of travel are being conducted. Measurements include attenuation rates and degree of coupling between wave types.

Gravity studies

Continental measurements--U. S, Coast and Geodetic Survey (A. J. Hoskinson, and D. Rice): Using a Helmholtz coil to stabilize the magnetic field around the Brown invar pendulum apparatus, a series of new gravity measurements were made at Brownsville, and Houston, Texas; Tulsa, Oklahoma; Beloit, Kansas; Huron, South Dakota; and Fairbanks, Alaska. Four of these stations were reoccupations of the line of pendulum bases set in 1952 for calibration purposes. Regional gravimeter coverage with stations at a 3- to 5-mile interval was established over the northern half of Georgia, western Illinois, and most of Iowa. Other areas that have been similarly mapped include a part of southern New Mexico, eastern Oklahoma, southern Kansas, central Tennessee and western Kentucky. Through an arrangement with Pan American Airlines, a series of gravimeter connections were made between New York City and Rome, Italy in cooperation with the Geophysical Institute of Trieste.

Dominion Observatory, Canada (G. Garland): The Cambridge University (England) pendulums compensated for changes in the Earth's magnetic field with a Helmholtz coil were used to establish a new tie between Ottawa and Teddington, England, and Ottawa and Washington. These pendulums were also used to occupy the sites established by the Woods Hole-University of Wisconsin group (G. P. Woollard, and J. C. Rose) using the Gulf Research and Development Company quartz pendulums between Mexico City and Houston, Texas, and between Lethbridge, Alberta, and Fairbanks, Alaska. The Tulsa, Oklahoma; Beloit, Kansas; Huron, South Dakota; and Winnepeg, Saskatchewan, bases established by the U. S. Coast and Geodetic Survey were also occupied as was the University of Wisconsin base at Madison, Wisconsin. The Dominion Observatory regional gravimeter coverage included a traverse along the Alaska Highway and Haines Highway and observations on an areal basis west of Hudson Bay north to Chesterfield Inlet. A gravimeter tie was also established between Ottawa and Washington.

University of Toronto, (J. Tuzo Wilson): A gravitational study of a large portion of the Grenville geological province of Ontario has been completed.

Ohio State University (W. Heiskanen): A regional gravity survey of the entire state of Ohio with gravimeter stations at 3- to 5-mile intervals on all the principal roads has been completed.

Indiana University (Judson Mead): A regional gravity survey of the state of Indiana has been completed and a Bouguer anolmaly map prepared with a companion magnetic anomaly map based on aero-magnetic data secured by the U. S. Geological Survey.

Michigan School of Mines (L. Bacon): A regional gravity survey has been completed over the Upper Peninsula of Michigan. Several detailed studies also have been conducted as to the applicability of gravity methods in prospecting for iron ores.

Harvard University (F. Birch): Four thesis studies involving the use of gravity as a method of studying geology are in progress. The areas include southern Quebec (M. Fitzpatrick), Vermont (W. M. Diment), the Sierra Nevada (H. Oliver), and the San Joaquin Valley of California (P. E. Byerly).

University of Wisconsin (G. P. Woollard): Two world-wide gravity studies are being conducted from this university in collaboration with the Woods Hole Oceanographic Institution. One, the establishment of a world network of gravimeter bases to serve as a framework for getting a more precise adjustment of the world's gravity data, has resulted in over 3000 gravity bases in 85 countries (see Figure 5). The only other comparable effort is that of Expeditions Polaires Francaises which has established gravimeter bases in both the Arctic and Antarctic regions as well as in Europe, Africa, southern Asia, and Australia.

The second program is the establishment of a series of precise pendulum gravity bases for calibration purposes and reference points. The quartz pendulums of the Gulf Research and Development Co. are being used and to date a series of bases have been established in North America between Paso Cortez, D. F., Mexico and Fairbanks, Alaska, and another series in Europe between Oslo, Norway, and Tripoli, Libya. A loop of observations around the world was also carried out in 1954.

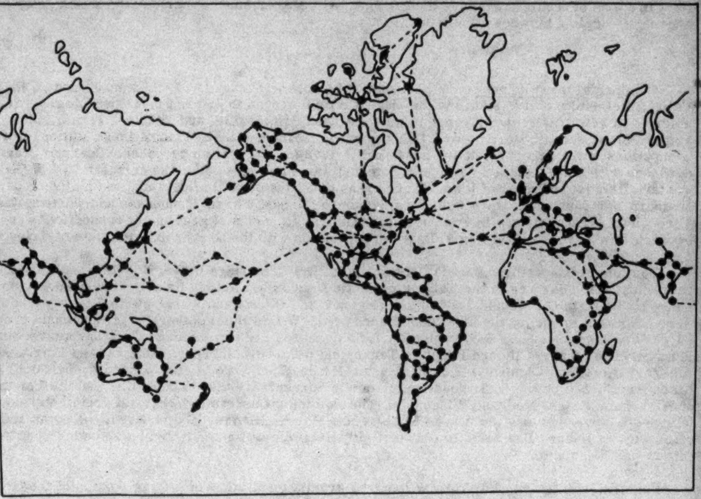


Fig. 5--World network of gravimeter bases established by Woods Hole Oceanographic Institution and University of Wisconsin

As part of the committee program for building up a regional gravity anomaly map of the United States to aid in studying the regional geology of the continent, a regional reconnaissance network of gravity and magnetic observations is being established over the country by the group at the University of Wisconsin. Figure 6 shows traverses established to date along which observations have been made at 10- to 12-mile intervals. In connection with this program, the committee chairman is again approaching oil companies for data to fill in holes in the present coverage. Figure 7 indicates the present status of coverage. Any data that would add to the coverage shown in Figure 7 would be greatly appreciated. The density of values in the solid areas is equivalent to that for a 8-10 mile grid of stations.

Thesis investigations include areal gravity surveys in connection with geologic investigations of the Baraboo Syncline, Wisconsin (W. Hinze), the Lake Superior-Kansas High (W. A. Black), the Des Plains Complex, Illinois (R. Pemberton), the Blue Mounds Caves, Wisconsin (A. Amante), and the Lake Superior Syncline (E. C. Thiel).

U. S. Geological Survey (J. Balsley): As part of an overall study of the Colorado Plateau region a regional gravimeter survey is being made. A similar study is also being made in the Mohave area of California.

Cambridge Research Center, U. S. A. F. (A. Crary): To supplement gravity values taken earlier on Fletcher's ice island while drifting across the Arctic Ocean, it is planned to resume observations on this island again this year.

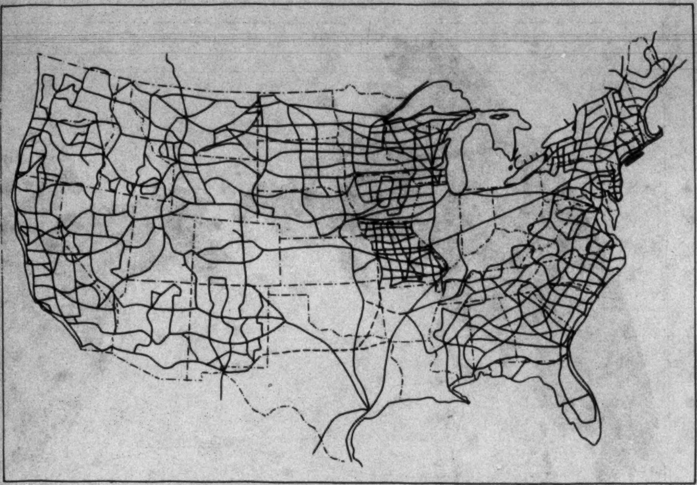


Fig. 6--Network of gravimeter traverses in United States established by University of Wisconsin

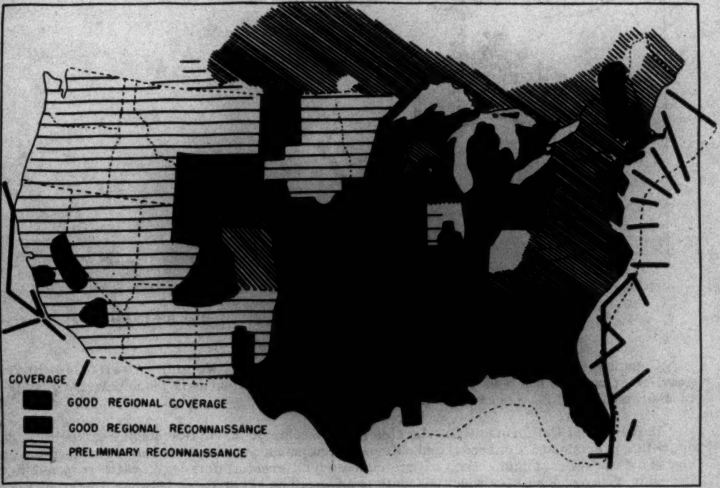

COVERAGE
GOOD REGIONAL COVERAGE
GOOD REGIONAL RECONNAISSANCE
PRELIMINARY RECONNAISSANCE

Fig. 7--Gravity coverage in United States

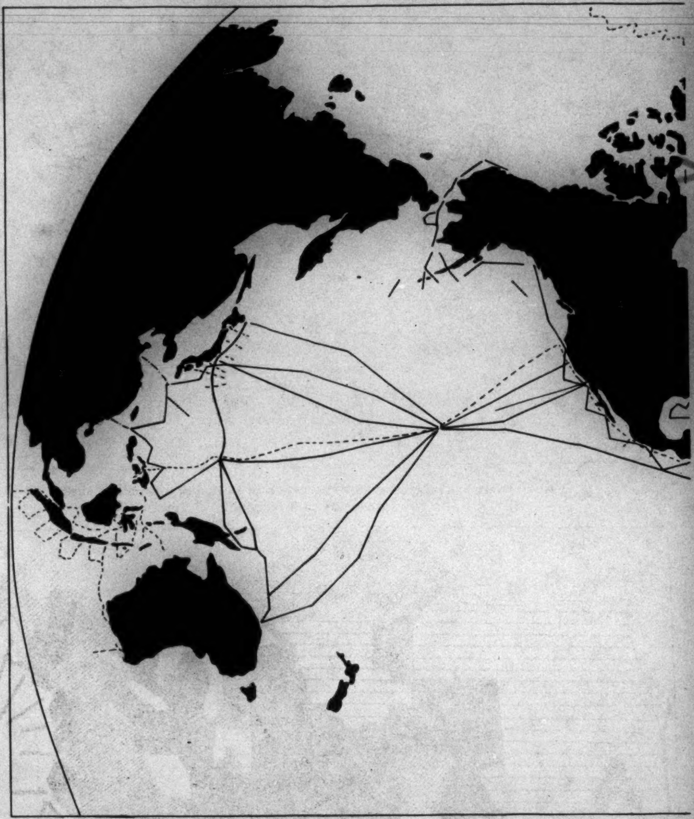
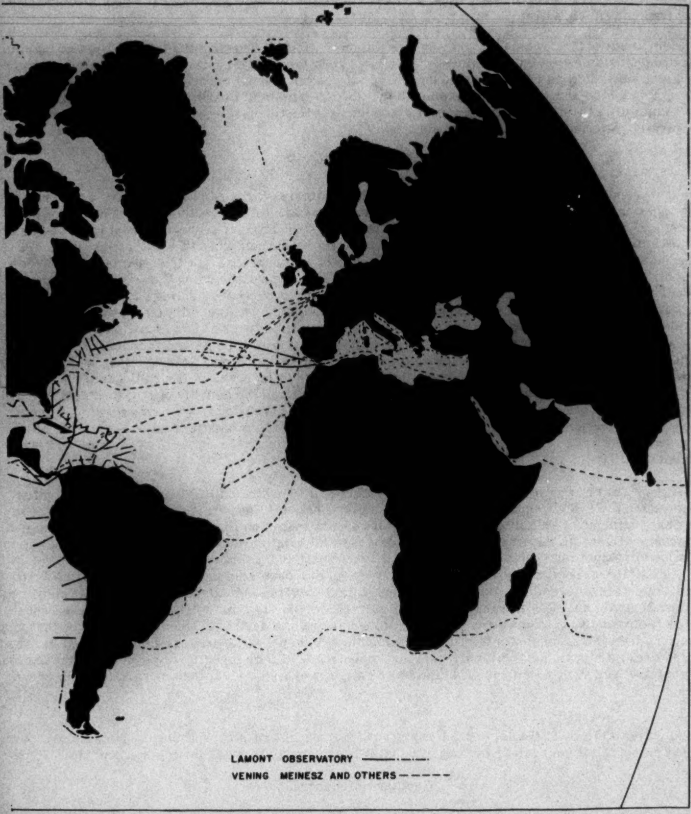


Fig. 8--Location of submarine

Columbia University, Lamont Geological Observatory (J. L. Worzel): A series of over 500 gravimeter stations has been established on Puerto Rico to supplement the submarine gravity measurements that have been made in the adjacent sea area.

University of California at Los Angeles (L. B. Slichter): Earth tide studies are being carried out with a precision of a microgal and automatic equipment perfected for both recording and processing the observational data. Data to date indicate a differential time lag in earth response to tidal forces in different localities which amounts to as much as 120 minutes between Austin, Texas, and Attu in the Aleutian Islands.



gravity traverses

Submarine gravity measurements--Lamont Geological Observatory of Columbia University (J. L. Worzel): Submarine gravity measurements have been made using Vening Meinesz pendulums along most of the commonly used navigational tracks across the Pacific Ocean via Oahu to Tokyo, Guam, and Brisbane, Australia. Observations have also been made along the Pacific coast of South and North America from Cape Horn to Alaska with detailed studies over such features as the Nippen Trench, the Marianas Deep, the Aleutian Trench and the South America Trench. In the Atlantic area two trans-Atlantic traverses have been run with detailed studies in the Bahama-West Indies region. The Continental Shelf of the United States has also been studied as has the north coast of South America. In Figure 8 the approximate location of these traverses along with the earlier ones of Vening Meinesz and the more local studies by others as around England and in the Mediteranean area are shown. The significant thing brought out by this map is the need for more gravity information in the oceanic areas.

University of California at Los Angeles (Slichter L. B.): Through the loan of a set of marine gravity pendulums by Vening Meinesz it has been possible to start a program of gravity measurements at sea. Studies carried out to date have all been of a local nature such as the investigation of the Mendocino and Murray Escarpments and investigations of nearby sea mounts. A study as to the adaptability of the vibrating spring submarine gravimeter developed by Gilbert (Cambridge University, England) is also being made.

Radioactive studies

It is reported by P. M. Hurley that several laboratories throughout this country are continuing investigations related to the determination of geological age by radioactive methods. In the U. S. Geological Survey it has been demonstrated that accessory zircons separated from igneous rocks can be used for age determination on the basis of total lead/uranium + thorium ratios and there appears to be good evidence that negligible amounts of common lead are included in these zircon structures at the time of crystallization. Also work is being continued on the isotopic abundances of lead extracted from uranium ores, and in galenas, and in carbon-14 dating. At the University of Chicago various investigators are studying age methods using isotope-dilution techniques for the measurement of lead and argon ratios. Carbon-14 measurements are being made on a routine basis, both with new and varied samples of material and with new instruments and techniques. A group at the University of Toronto is continuing a survey of the proportion of lead isotopes in lead minerals of various ages, with interesting observations on the rate of increase of the radiogenic nuclides with the time of crystallization of the samples which throw light on the genesis of ore leads and the relationship between uranium, thorium and lead in the crust and mantle, as well as providing a means of age determination for the galena samples. Over 300 age determinations have been made so far with specimens representing 27 geologic provinces. The Toronto group is also working on argon-potassium ratios.

A group at the Carnegie Institution's laboratories in Washington has been continuing studies of the ratios Sr^{87}/Rb^{87} and A^{40}/K^{40}, as well as lead ratios in minerals. At the Lamont Geological Observatories of Columbia University, work is continuing on lead ratios and on the causes of disagreement such as radon escape. The group has also continued carbon-14 dating and the use of unsupported ionium and radium in ocean cores as means of time measurement in sediments. At the California Institute of Technology the geochemistry group has been studying the variation of the isotopic abundances of lead in sedimentary material and in meteorites. An extraordinarily low proportion of the radiogenic nuclides in samples of lead extracted from iron meteorites has given the best figure for the primordial abundances of lead isotopes as well as added evidence on the age of the solar system. At the Massachusetts Institute of Technology isotope variations are being studied in strontium and calcium in terrestrial materials and meteorites. Other investigations in these laboratories include total lead ratios in zircons, helium age ratios, and radium and ionium variations in ocean cores.

As part of the U. S. Geological Survey program several areas throughout the country are being studied as potential sources of radioactive materials using airborne detection equipment.

Geothermal studies

Continental studies--Francis Birch reports that studies of temperatures and conductivities intended to give estimates of heat flow in borings and salt mines in Michigan are being carried out by James T. Wilson, University of Michigan. A determination of heat flow in the Calumet Peninsula of Michigan has recently been published [F. BIRCH, Amer. J. Sci., v. 252, pp. 1-25, 1954]. Geothermal investigations are being continued near Point Barrow, Alaska, and at several other Alaskan localities, by members of the U. S. Geological Survey, and hopes have been raised for studies by Survey parties of temperatures and heat flow in the Colorado Plateau. Studies of conductivity by Sydney Clark of several collections of samples of rocks from the vicinity of Swiss tunnels are in progress at Harvard University. These results have been substantially augmented by additional measurements by E. R. Niblett at the University of Toronto of independently collected samples from the Simplon and Saint Gotthard regions. At Kemano, British Columbia, the University of

Western Ontario has been conducting measurements in a tunnel of the Kitimat power project. Of special interest is the method being used by this group to measure thermal conductivities in situ.

Marine studies--The most significant recent development in geothermal studies has been the determination of heat flow at sea, by Bullard, Revelle, and Maxwell. A complete description of apparatus and methods, and five determinations for the eastern Atlantic, have now been published by BULLARD [Proc. R. Soc., A, v. 222, pp. 408-429, 1954]. A preliminary report with six determinations in the central Pacific has been published by REVELLE and MAXWELL [Nature, v. 170, pp. 199-200, 1952]. Nine additional determinations were obtained on the Capricorn Expedition of the Scripps Institution. Of these, three measurements were on the continental side of the andesite line. Two had higher than average values while the third value was average. Just as large deviations were observed on the seaward side of the andesite line.

At present, there appears to be no systematic difference between oceanic and continental values of heat flow, a most important, if tentative, conclusion. All of the marine measurements were made with short probes in the bottom mud, at depth of between 2000 and 5000 meters. An independent determination may be obtainable from the results of the Eniwetok borings, where temperature measurements were made by J. H. Swartz of the U. S. Geological Survey. Conductivities of samples from these drill-holes are being studied at Harvard and should permit an estimate of minimum conducted heat.

Magnetic studies

Continental studies--E. B. Roberts reports that the U. S. Coast and Geodetic Survey magnetic observatory at Cheltenham, Maryland, will soon be superseded by a new observatory and laboratory at Fredericksburg, Virginia. New magnetic charts of the world and of the United States and Canada for epoch 1955.0 are now complete for D, H, I, Z and F. Magnetic surveys in Central and South America are being continued under the auspices of the Inter-American Geodetic Survey. To date more than 40,000 miles of track have been covered using the U. S. Hydrographic Office airborne magnetic equipment. These data have proved satisfactory for use in magnetic cartography. In Canada, many of the mining areas in New Brunswick, the Grenville area of southern Ontario and the ultrabasic area of southern Quebec are now covered by aeromagnetic surveys conducted by the Geological Survey of Canada.

U. S. Geological Survey (J. Balsley): Although the extensive aeromagnetic surveys conducted by the U. S. Geological Survey using total-intensity equipment are being reported elsewhere, Figure 9 shows the location of areas surveyed and traverses run to date. Information concerning specific areas can be secured on application to the Survey. Progress is being made on the preparation of a magnetic-anomaly map for the Coastal Plain region of the state of Georgia which should be available during the year.

Marine magnetic measurements--T. Miller and R. Revelle report that although several aeromagnetic traverses have been made over oceanic areas in recent years (see, for example, Fig.9), the most extensive series of surface observations taken since the loss of the Carnegie are those taken by the groups at the Lamont Geological Observatory and the Scripps Institute of Oceanography. Using a total-force magnetometer from an airborne unit mounted in a fish to tow astern of a surface vessel, over 18,000 miles of traverse have been run by the Lamont group, including a trans-Atlantic traverse. The Scripps group, using the same instrument, have established 7800 miles of traverse in the Pacific.

Other marine studies

J. L. Worzel reports that the bottom coring program being carried out by the Lamont Geological Observatory, the Woods Hole Oceanographic Institution, and the Scripps Institute of Oceanography has resulted in several hundred long cores. Analyses of these cores will add materially to knowledge on marine sedimentation. The greatest concentration of cores taken to date has been in the Gulf of Mexico.

Electrical studies

At Pennsylvania State College (M. L. Keith, and B. F. Howell, Jr.), measurements are being made on the dielectric constants of dry rocks and minerals over the frequency range from 200 to 30,000,000 cps. Measurements are also being made as to the effect of moisture content. Research

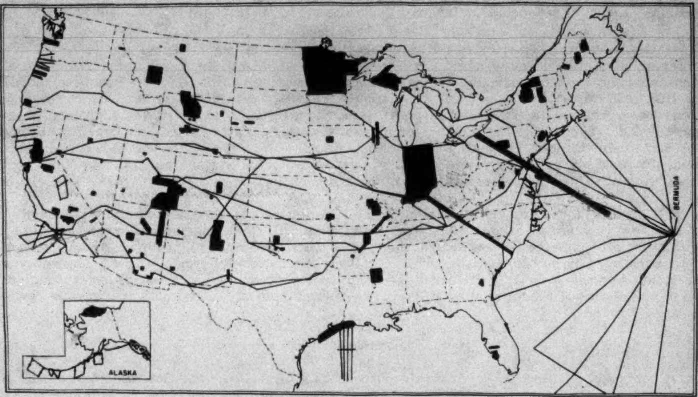


Fig. 9--Areas studied by the U. S. Geological Survey using aeromagnetic observations

as to the effect of variations of oil and water saturation on the electrical resistance of rock is also being carried out along with the effects of rock pressure and fluid pressure.

Tectonic measurements

U. S. Coast and Geodetic Survey (E. B. Roberts): Repeat triangulation and leveling measurements in the Bakersfield-Tehachapi area of California show that following the earthquake of July and August of 1952, there was a horizontal displacement of up to two feet and vertical movements up to four feet. Precise leveling studies between the United States and Canadian level networks in the vicinity of the Great Lakes in connection with the St. Lawrence seaway and an analysis of earlier data indicate a differential tilt amounting to 0.5 feet per 100 miles per century in a direction 30° east of north.

Concluding remarks

Although it has not been mentioned specifically, most of the activity indicated in this report has been possible only through government support. In particular the Office of Naval Research has played a most significant role by contributing funds and supplies, and making available military transportation for many of the projects listed. Similarly much of the work cited could not have been possible without the support of the Cambridge Research Center of the Air Force. However, the importance of the more limited support received from private organizations such as the Geological Society of America and other groups with limited funds should not be underestimated. In many cases the pilot work for some of the major studies reported was all done under a grant-in-aid from a private organization, and without this start, it would not have been possible to enlist government support for the more extended studies.

University of Wisconsin,
Madison, Wisconsin

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REPORT OF THE COMMITTEE ON INFILTRATION, 1953-1954

Leonard Schiff, Chairman

1954	1955	1956
L. L. Kelly	E. H. Kidder	Howard L. Cook
Wm. P. Martin	P. B. Rowe	Howard W. Lull
Howard Matson	N. L. Stoltenberg	Donald E. Whelan

Reports from the Committee and others follow in abstract. The Chairman has complete reports on file.

V. S. Aronovici (Agricultural Research Service, Pomona, Calif.)--Two papers are in preparation. The first, The Application of the Ring Infiltrometer to Diagnosis of Irrigation Problems in Southern California [1954], indicates that the one-square-foot ring infiltrometer of conventional type is not suited to quantitative evaluation of irrigation-furrow performance but does provide qualitative values. The conventional ring infiltrometer does not duplicate the gravity and suction head forces involved. The second, Model Studies of the Ring Infiltrometer under Low Initial Soil Moisture, illustrates the significance of the suction head produced by the capillary potential gradient between the wet-dry soil interface and the base of the soil column confined within the ring; and further indicates the relative influence of profile conditions, initial soil moisture, ring depth, and diameter upon rates. More recently, observations made in citrus orchards using the Fred Hamilton type furrow infiltrometer, which permits lateral flow, appear to compare favorably with the furrow.

H. O. Banks (California State Division of Water Resources, Sacramento, Calif.)--A final report on an inventory of all artificial recharge activities and projects in the State covering location, water rights, spreading system, control works, measurements, geologic, hydrologic and soils data, rates of percolation, and costs is planned for publication during the fiscal year 1954-1955.

Stream-bed percolation studies have been made in Putah Creek (1) by direct current meter measurements of channel percolation losses and (2) by inflow-outflow relationships of existing gaging stations. A thorough study of geology and sub surface structure in relation to ground-water recharge from Putah Creek has been made.

In cooperation with the U. S. Geological Survey and the U. S. Bureau of Reclamation, percolation measurements have been made on eight streams on the west side of the valley north of Sacramento to determine the amounts of infiltration of surface water to ground water. Percolation measurements have been made on ten streams on the west side of the San Joaquin Valley from Newman to Coalinga.

Paul Bauman (Los Angeles County Flood Control District, Los Angeles, Calif.)--Biennial reports on hydrologic data, including sections on rainfall and runoff and covering data on seasonal rainfall, outstanding storm rainfall, summaries of daily runoff, and normal storm water-spreading activities are published and available on loan from the District. Infiltrometer experiments to determine rainfall-runoff relationships for various geologic formations and soil classifications are nearly completed. Unpublished results are available in the District office. A comprehensive investigation of the conservation possibilities of the San Gabriel River system is being made, which will include consumptive use and pumping draft, infiltration to ground-water basin by rainfall, stream flow and spreading of local water, imported water and reclaimed sewage, and all other items entering into a water balance for the river system.

BAUMANN [1952] published a paper on Ground-Water Movement Controlled Through Spreading. In 1950 the District initiated a test program of infiltration of fresh water near the shore line of the ocean to determine the possibility of halting or minimizing sea-water intrusion into fresh water aquifers which is discussed in an unpublished report by Laverty, Jordan, and van der Goot. Published articles on these tests are by LAVERTY [May, August, 1952] and BAUMANN [1953].

Articles have been published cooperatively with the District on the reclamation of sewage and industrial effluents by spreading by ARNOLD, HEDGER, and RAWN [1952].

E. A. Colman (California Forest and Range Experiment Station, Berkeley, Calif.)--A book dealing with infiltration discusses the processes and reviews research on vegetation influences [COLMAN, 1953].

George Craddock (Intermountain Forest and Range Experiment Station, Ogden, Utah)--A paper is being prepared by H. F. Haupt describing nitrogen losses from surface soil, incurred during infiltrometer runs. These nitrogen losses increase with increases in amount of runoff and soil losses and with decreases in soil cover. The nitrogen losses also increase with increases in soil disturbance (artificial trampling), even on well-covered areas. Paul Packer is preparing a description of the intermountain infiltrometer which supplies water from F-type nozzles over a 6 x 6 plot, subdivided so that runoff and soil loss are measured from three 2 × 6 plots. This method provides more data at a lower manpower cost.

Wayne D. Criddle (Agricultural Research Service, Logan, Utah)--Ring infiltrometers are being used in an attempt to correlate the results with rates of intake from furrows, flood irrigation, and sprinkler irrigation. The swinging can infiltrometer is being used to obtain design information for sprinkler irrigation systems. Irrigation trials under a variety of conditions are being conducted by the Soil Conservation Service; however, further study is needed before reports can be made on this work.

William W. Donnan (Agricultural Research Service, Los Angeles, Calif.)--A study was made in Zone 3 of Ventura County, California, on the Calleguas Creek and Conejo Creek watersheds, and in Pleasant Valley and West Las Posas, to determine the annual rainfall and irrigation water penetration for the purpose of ground-water replenishment. Analyses were made to determine the average annual recharge. Successful replenishment of ground water by water spreading depends on a rapid rate of permeability throughout the entire soil profile down to underground aquifers. Those areas having infiltration rates of less than one foot per day should be considered only under extreme necessity.

E. J. Dortignac (Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado) --The Rocky Mountain infiltrometer [DORTIGNAC, 1951] was used in more than 160 tests during 1952-1953 to measure infiltration and erosion rates from reseeded and adjacent native vegetation range lands under grazing and non-use in north-central New Mexico. About 40 infiltration-erosion field tests were conducted as part of a study to evaluate range-watershed conditions, trend, and potential on major vegetation zones on northern New Mexico. Further studies are planned over a period of years. Preliminary findings will be presented in the annual reports of the Rocky Mountain Forest and Range Experiment Station.

F. R. Dreibelbis (Agricultural Research Service, Coshocton, Ohio)--A report of preliminary studies on soil conditioners as they affect the hydrology of small watersheds has been prepared by F. R. Dreibelbis, R. E. Youker, and L. L. Harrold. Information on this report may be obtained by contacting Mr. Dreibelbis. Data found from five areas, each representing a different treatment, are included along with a study of soil moisture and properties that affect soil water movement. Data obtained from other powder and liquid treatments on small plots should aid in evaluating the usefulness of soil conditioners and their effect.

A. E. Erickson (Michigan State College, East Lansing, Michigan)--Concentric ring infiltrometers are being used to measure infiltration on a hundred typical sites representing 30 soil types The infiltration data secured from this project, in conjuction with the other physical and chemical studies, should be of value in making recommendations to the farmers of Michigan.

L. L. Harrold (Agricultural Research Service, Coshocton, Ohio)--A subsoiling operation was performed to increase the transmission of water to greater depths beneath the soil surface and thus to improve infiltration capacities of farm land. Krilium was blown into the subsoiled area to stabilize the shattered conditions. Undisturbed core samples will be used for permeability determinations. Observations will continue on this work.

J. C. Holland (Northern Rocky Mountain Forest and Range Experiment Station, Missoula, Montana)--Infiltration tests were made in 1952 on a timbered site and a burned site on Upper West Branch Creek, Kaniksu National Forest, in northern Idaho, as described in Research Note 127, October, 1953. Artificial rainfall on two plots at each site was applied with a Rocky Mountain infiltrometer. Rainfall application and runoff on the test plots were summarized. Lower infiltration on the burned site is attributed to the lack of protection against the puddling effects of raindrops.

Don Kirkham (Iowa State College, Ames, Iowa)--Results of experiments with a chemical (PR-51 made by the Atlantic Refining Co., Philadelphia) in increasing infiltration rates in soil were not large enough to reach the five pct level of significance; however, a field for this type of chemical, which is not a soil conditioner, is indicated. Work on the effect of soil anisotropy in certain types of infiltration measurements by Marinus Maasland should be published soon.

Howard W. Lull (U. S. Forest Service, Vicksburg, Miss.)--Results of infiltration studies at Vicksburg, Mississippi, have been published by REINHART and TAYLOR (1954). These studies emphasize the importance of antecedent available storage capacity upon infiltration rates and amounts for certain fine-textured soils.

Howard Matson (U. S. Soil Conservation Service, Fort Worth, Texas)--Families of curves were developed relating volume of runoff to volume of applied simulated rainfall on 200 infiltrometer plots. Curves in each family were found related by soil texture and depth, type and amount of cover, and extent of applied conservation practices. A composite curve was drawn for each family of curves and represents a soil-cover complex. The amounts of runoff which would be produced by the application of specified volumes of simulated rainfall to each soil-cover complex were determined from the appropriate composite curve and expressed as a decimal or mixed decimal of the runoff from one of the soil-cover complexes. Relative factors thus derived are used to determine the incremental runoff from a gaged watershed, to estimate the runoff from an ungaged watershed by relating the soil-cover complexes to a nearby gaged watershed, or to compute the reduction on surface runoff that may be expected from conservation treatment.

Louis J. Metz (Southeastern Forest Experiment Station, Union, S. C.)—The effect of fire on the infiltration rate of forest soil in the Piedmont region is being studied by the Southeastern Forest Experiment Station. To date the work has been concerned with the effect of drop fall on soil movement and the raindrop size distribution of simulated and natural rains.

Leonard Schiff, Eldred S. Bliss, and Curtis E. Johnson (Agricultural Research Service, Bakersfield, Calif.)--Investigations are being continued on soil treatments and operational procedures that increase infiltration rates. Among them are: Vegetative - cotton gin trash and Bermuda grass; chemical - Krilium, Orzan, Flotal; mechanical - injection shafts and injection ditches; and operational - depths and location of treatment, size and shape of spreading areas, arrangement of areas, length of incubation and drying periods, cultural operations, and surface head. A paper covering these phases with emphasis on soil permeability and size of areas has been published, [SCHIFF, 1954].

Norman R. Tripp and Donald E. Whelan (U. S. Forest Service, Philadelphia, Pa.)--A report of the effect of manipulation of vegetative cover and land management on surface runoff and streamflow has been presented. Theories have been worked out on the established basis that; Regulatory effect of watershed lands on waterflow is a function of infiltration capacity of watersheds; infiltration capacity is a composite of infiltration capacity of soil and cover conditions; future runoff can be predicted by known changes in land use and conditions if contributions of soil-cover complex are known. The evaluation procedure has been reported by TRIPP and WHELAN [1953] in mimeograph form. They state that additional work and field tests are needed, but once worked out, should prove valuable in future work.

George T. Turner (Upper Colorado River Research Center, Delta, Colorado)--Studies were made using the Rocky Mountain infiltrometer on 21 sites at four locations to evaluate range and watershed conditions of several plant-soil complexes. Results indicate the plant cover present is a good indicator of both range and watershed conditions. A report is planned on this study. A study was made in 1953 to determine the effect of livestock exclusion on erosion and runoff from salt-desert shrub lands in western Colorado. Infiltration rate and erodibility tests were made on eight watersheds, four of which will continue to be grazed and four fenced to exclude livestock. These tests will continue to be made at five-year intervals for 20 years.

L. R. Wohletz (U. S. Soil Conservation Service, Berkeley, Calif.)--Greater use of 12-inch ring infiltrometers is planned: as a tool in irrigation layout planning, as a means of evaluating the benefit of various agronomic practices in improving the infiltration rate of soils difficult to irrigate, and as a means of evaluating the performance of various chemical amendments, such as Krilium, PR-51 and PR-78, and Pent-a-vate, that have been applied in San Benito County.

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Transactions, American Geophysical Union Volume 36, Number 4 August 1955

PROGRESS REPORT, SEISMOLOGICAL LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY, 1954

H. Benioff, B. Gutenberg, and C. F. Richter

(Contribution No. 710, Division of the Geological Sciences,
California Institute of Technology, Pasadena, California)

Station development

New equipment--A long-period Benioff vertical component seismograph ($T_0 = 1$ sec, $T_g = 90$ sec) has been installed in the Riverside station, and a second horizontal component with similar constants has been added at Tinemaha. At Pasadena two three-component sets of strong motion torsion instruments designed by F. E. Lehner are now recording on film. These have periods of approximately 0.8 sec and damping nearly critical. The effective magnifications, when viewed with a projector giving 8× magnification, are 100 and two respectively. On July 9 the six-second period torsion instruments at Pasadena were rotated to record N 45° W and N 45° E.

The Haiwee station has been converted to film recording. Equipment and housing at Isabella and Fort Tejon have been improved. Crystal clocks are now in operation at Pasadena, Mount Wilson, Riverside, Barrett, and Tinemaha.

Station coordinates--Using new maps, station coordinates have been revised. Changes are minor except at Tinemaha for which correct coordinates are 37° 03.3′ N, 118° 13.7′ W; elevation 1195 m.

Instrument development

Recorder for magnetic field fluctuations (H. Benioff)--An experimental assembly has been in operation several months for recording the rate of change of the Earth's field in the approximate frequency range five to 1/5 cycles per second. The apparatus consists of a large coil of wire connected to a seismograph recorder having a galvanometer of 1.4 sec period and a recording speed of one mm per second. The purpose of the experiment is to investigate possible relations between magnetic field variations and the occurrence of short-period microseisms in the range 0.5 to two seconds periods which are frequently associated with rain.

Transistor operation of the carrier current variable discriminator (H. Benioff and J. L. Blayney)--The carrier-current variable discriminator seismograph described in preceding reports is now modified to operate with a crystal-controlled transistor oscillator in place of the tube oscillator used with the earlier design. The carrier frequency is 100 kilocycles per second. The device uses one transistor as an oscillator and an additional transistor as amplifier. The output of the amplifier is two volts, and when coupled to the discriminator produces a dc output of 20 volts across each of the diode resistances. Silicon diodes have been substituted for the germanium diodes of the earlier design. These permit operation of the output circuit at higher impedance with consequent reduction in the size of the coupling condenser for a given time-constant. The transistors operate from hearing-aid type batteries of 1.34 volts for the oscillator and 2. 68 volts for the amplifier. The battery current drain is so small that the operating life on one set of batteries is approximately one year. The use of transistors has resulted in great simplicity of design, with consequent reduction in size of the electrical components. Moreover, it renders the instrument except the recorder completely free of external power sources.

Low magnification torsion seismometers (F. E. Lehner)--Vertical and horizontal component torsion seismographs with effective magnification of 2, 4, and 100, when viewed with an 8× projector, have been completed. They have inertia reactors in the form of coils suspended in a magnetic field. Damping is adjusted by varying an external resistance shunting the coil. Opening the circuit undamps the movement for period measurement without changing the magnetic field. Test deflections are made by applying small E M F s across the coil through a high resistance. The lower magnification instruments are modified for the vertical component response by mounting with the suspension horizontal and twisting it into position. The 100× vertical instrument is mounted with the suspension horizontal, but with the weight of the coil supported by a spring arranged so as not to affect the period (Fig. 1).

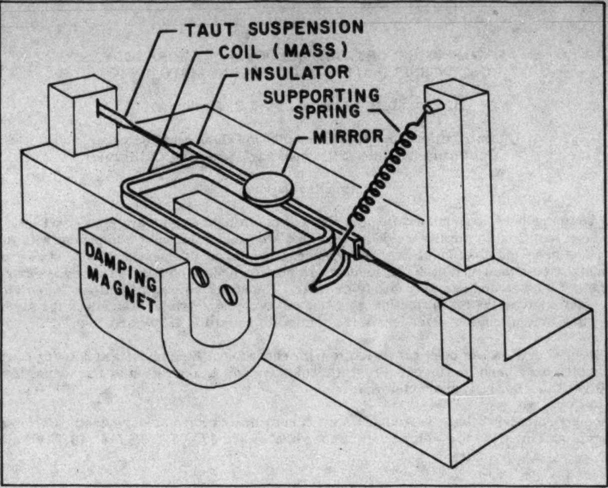

Fig. 1--Low-sensitivity, vertical-component, torsion seismometer (schematic)

Ultra long period galvanometer (F. E. Lehner)--A method has been developed for increasing the period of galvanometers by introducing a negative restoring force to neutralize part of the restoring force of the suspension. A small piece of magnetic material (0.001-inch dia. wire 0.03-inch long) is mounted on the coil tab, outside of the principal field and located in, and at right angles to, a weak auxiliary field. Two 90-second period galvanometers have been supplied with this modification and are operating with Benioff strain seismometers at periods of 200 seconds. Periods of five minutes have been attained experimentally.

Project sponsored by the Geophysics Research Division
of the Air Force Cambridge Research Center

In association with the auxiliary seismological station at Palomar, the following instruments are in operation:

(1) A tripartite net consisting of three Benioff vertical-component reluctance seismometers with ten-second period galvanometers recording with adjacent traces on a single drum having a paper speed of three mm per second and automatically set into operation for approximately five minutes each hour.

(2) N-S, E-W and combined (N-S) + (E-W) strain seismographs recording on a single drum as in the preceding.

(3) N-S and E-W Benioff moving conductor seismographs, T_g = four seconds, T_o = 1.5 seconds recording as in the preceding.

(4) A vectorial recorder in which the responses of a vertical component pendulum and an (E-W) + (N-S) strain combination provide the two vectors respectively.

Correlated study of records of all these instruments indicates that the majority of microseisms are movements having the vibration characteristics of Rayleigh waves. They probably represent some form of channel wave. Microseisms having properties of shear waves are occasionally observed.

Magnitude-energy relation

The Richter magnitude scale is well established as a consistent means of rating earthquakes, and is a valuable statistical tool. Serious difficulties have arisen in attempting to relate magnitude M to energy E. Unfortunately, adequate means have not yet been applied to establish an absolute scale of energy with a one to one relation to magnitude. This would entail removing the partly arbitrary definitions of the magnitude M, for example, by defining $M = A + B \log E$ and selecting A and B in such a way that for the most frequently used magnitudes the new values of M differ as little as possible from those now in use.

The equations

$$\log E = 11.3 + 1.8\,M \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

and

$$\log E = 12 + 1.8\,M \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

used by Gutenberg and Richter [1942, p. 180; 1949, p. 10] give too large values for the energy. For a short time, the equation

$$\log E = 11 + 1.6\,M \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

was preferred by the authors [as mentioned by Gutenberg and Richter, 1954, p. 10]. However, it appears that log E cannot be connected with M by a single linear equation without making the energy of great shocks too large relative to the small ones. At present, on the basis of a provisional theory, Benioff prefers two linear equations, one for small and another for large magnitudes. For shallow shocks Gutenberg is working with

$$\log E = 9.4 + 2.14\,M - 0.054\,M^2 \quad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

with probably somewhat smaller energy for deep shocks. Further research on these problems is in progress.

Long-period waves (H. Benioff)

Several world transits of G waves recorded on a seismogram of the Kamchatka earthquake of November 4, 1952, written by the long-period strain seismograph (T_g = 180 sec) have indicated a wave speed of 4.38 km/sec corresponding to 152.3 minutes for a complete circuit of the Earth. No evidence of dispersion for these waves could be found.

Low-velocity layers (B. Gutenberg)

B. Gutenberg continued to study the various low-velocity layers in the Earth and selected the problem of their effects as subject of his presidential address at the meeting of the International Association of Seismology and Physics of the Earth's Interior in Rome on September 16, 1954 [GUTENBERG, 1954c]. Such layers and the channels produced by them play a much greater role in geophysical phenomena than it is realized by most geophysicists. The main indication for low-velocity layers is zones of relatively small amplitudes or even shadow zones. Misidentification of waves arriving in such zones can easily result in erroneous conclusions, which, like the spurious discontinuity at a depth of about 400 km, may enter other fields of the earth sciences as facts.

Three major low-velocity layers have tentatively been found to exist in the Earth's crust. Two of these, the lithosphere channels, are respectively in the 'granitic' and 'basaltic' ('gabbro') layer of the continents while a third channel extends possibly everywhere from the Mohorovicic discontinuity downward into the asthenosphere. In Figure 2 velocity-depth curves considered probable at the time of this writing (January, 1955) are indicated. All three channels are probably a consequence of the temperature increase with depth which produces a decrease in the elastic constants in excess of the increase due to increasing pressure. Phase changes may also affect the resulting wave velocities.

Several types of waves are believed to be guided by the channels in the crust, especially Pa and Sa by the asthenosphere channel, Lg1, Lg2, and Rg by the lithosphere channels; similar wave types guided by low-velocity layers in sediments must be expected. Many records of the Southern California earthquake of July 21, 1952, show channel waves with periods and velocities as reported for other earthquakes.

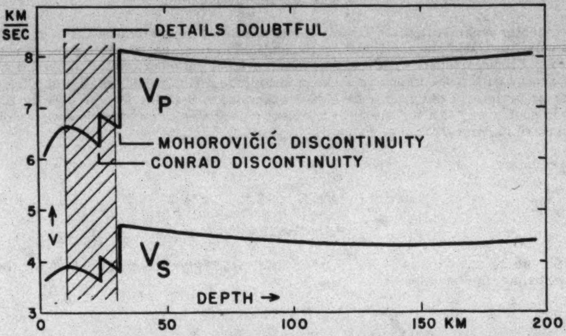

Fig. 2--Tentative velocities Vp of longitudinal waves and Vs of transverse waves in the Earth's crust after Gutenberg

The regular microseisms with periods of four to ten seconds have properties similar to those of the Lg - Rg group in earthquake records and are probably propagated by the same mechanism.

Geophysical elements in isostatic calculations (B. Gutenberg)

Calculations of the pressure in the Earth's crust were made by B. Gutenberg. Combining all data on temperature and pressure and their effects on the density of the rock types most likely to occur in the various portions of the Earth's crust under mountains, lowlands and deep oceans, it is concluded that at depths below about 50 km the pressure is the same in all these regions within the limits of error. This indicates the existence of isostasy. Calculation of the mean density of a column above the Mohorovicic discontinuity indicates that it is probably at least 0.1 greater than the value of 2.67 gr/cm^3 which is now used in isostatic calculations, and that the difference between the density of the material below the discontinuity and the average density above it is probably closer to 0.5 than to the value of 0.6 which is now in use. Portions of results of this research have been incorporated by W. Heiskanen in his report on 'Isostasy' to the International Geophysical Union meeting in Rome, on September 21, 1954.

Seismicity of the Earth

The second edition of the book bearing this title has appeared. It was possible to add a last-minute note on the earthquake under southern Spain on March 29 (depth 640 km), which calls for modification of language where it has previously been stated that all shocks deeper than 300 km occur in the Pacific area and the East Indies. The International Summary was used for shocks through March, 1942. The book lists shocks of magnitude 7 and over to the end of 1952. Only one shock of magnitude exceeding 7.9 occurred during 1953, and none in 1954.

Cataloguing of large shocks is being kept as close to date as possible. Revision of determinations, and investigation of additional shocks, is being carried forward as new issues of the International Summary appear (at the end of 1954, this included September, 1945).

Student research (C. F. Richter)

Robert Morrison has plotted travel times of P at Reno for the Kern County earthquakes. The delay of Pn due to the Sierra Nevada is two to three seconds depending on the particular epicenter. Delays up to four seconds, as for the main shock, which is among those farthest from Reno, probably indicate a second P phase with Pn not arriving at all.

Cinna Lomnitz has made a new independent determination of the station corrections to be made in applying the magnitude scale. These represent the normal deviation (with opposite sign) of the uncorrected magnitude determined from a given torsion instrument, with reference to the magnitude found from the mean of all such data. The resulting corrections are as follows (the second decimals have little significance):

	Pasadena	Riverside	Sta. Barbara	Haiwee	Tinemaha	Woody	Barrett
NS	+0.23	+0.18	-0.21	-0.04	-0.14	- - -	-0.18
EW	+0.14	+0.14	-0.24	-0.01	-0.26	-0.08	- - -

For the stations in operation on 1932, these are very close to the results found by Richter in that year, and to those independently determined by Gutenberg in 1945. The systematic difference between components persists, and cannot be altogether instrumental in origin.

Lomnitz prepared a catalogue of the shocks of the series of magnitude 4 and over near Fallon, Nevada, beginning July 6, 1954. Origin times and magnitudes were determined mainly from the data of the Southern California stations alone. The two large shocks on July 6 and August 24 were both tentatively assigned magnitude 6.8; however, magnitudes determined at different stations vary with azimuth in a different way for the two shocks; the magnitudes will eventually require a correction.

Lomnitz has made a detailed study of shocks in the Gulf of California and in Lower California, at distances ranging from 6 to 12° from our stations; he has established approximate travel time curves for P, Lg, and eG. The variation of amplitude A with distance Δ has been studied. The quantity $\log A + s - M$ was plotted as a function of Δ; A is the maximum amplitude in mm as recorded by the torsion seismometers, s is the station correction, and M is the magnitude. The plotted points fall regularly 0.1 to 0.2 units below the line representing the relation $\log A = 3.37 - 3 \log \Delta$, which was derived from data for shorter distances in 1934. The relation between log A and Δ appears to differ over structurally different paths. Points plotted for a few shocks off the coasts of northern California and Oregon fall systematically lower, by somewhat over 0.1 unit, than those for the Mexican shocks.

Observations of local and distant earthquakes (C. F. Richter)

Local earthquakes; Kern County and elsewhere--During 1954 statistics were continued for shocks of magnitude 3 and over originating in Southern California and Owens Valley. Separate count was maintained for aftershocks of the Kern County earthquake occurring within the sharply bounded area delimited by aftershock epicenters in 1952. The tendency of this activity to extend northeastward, apparent toward the end of 1953, did not develop further in 1954. Totals are:

Magnitude 5.0 and over	1953	1954
Kern County	0	3
Other	1	5
Magnitude 4.0 - 4.9		
Kern County	18	7
Other	26	27
Magnitude 3.0 - 3.9		Jan. 1 - Sept. 30
Kern County	198	104
Other	120	160

A large fraction of the shocks indicated as 'Other' occurred on and after March 19, 1954 in the Santa Rosa Mountains, as aftershocks of the earthquake on that date which was the only one exceeding magnitude 6.0 in Southern California during 1953 and 1954. The falling off in Kern County during 1954 was slow but steady, interrupted by conspicuous rallies in January and May.

During 1954 activity just outside the area of investigation was higher than average. This included two shocks near Fallon, Nevada, on July 6 and August 24, of magnitude near 6.8; many shocks in the Gulf of California (the largest on April 29, magnitude 7) and northern Baja California (largest on November 12, magnitude 6); and a shock of magnitude at least 6.5 off the northern California coast on November 25, one over 7 in Nevada on December 16 with spectacular faulting, and one about 6.6 on December 21 (destructive at Eureka, California).

Routine bulletins and reports--The regular bulletin on teleseisms and large local shocks has now nearly recovered from the delay caused by the Kern County earthquake emergency. It has been issued through 1952, and is in press for January 1 - August 24, 1953. Reports on local shocks are nearly up to date, supplemented by special listing of the larger Kern County shocks.

Visitors

K. E. Bullen, Professor of Applied Mathematics in the University of Sydney, was in residence as visiting professor for three months. Miss I. Lehmann of Copenhagen was in residence for about four months.

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DISCUSSION OF

"A METHOD OF ESTIMATING PRECIPITATION NORMALS FOR SHORT-RECORD STATIONS"

by JAMES C. COFFIN

[Trans. AGU, v. 35, pp. 405-412, 1954]

Shuh-Chai Lee (National Taiwan University, Taipei, Taiwan, China)--Coffin's method seems a good tool in estimating monthly precipitation normals of short-record stations if the following modifications are added.

(1) In order to obtain the most representative normals $\bar{y}$ of stations used in regression, the data y's of every long-record station should be tested as to whether they can give the best estimate. In other words, what number of years, say $N = 32$ or more or less, may sufficient to guarantee a desired accuracy e in per cent of normal?

(2) A similar test must be applied to regression line, $Y = a + bx$, of normals $\bar{y}$ on means x of a particular period, say, ten or five years, to determine the sufficient number of pairs of values, that is, number of stations $N = 11$, or more or less required.

The test formulas suggested by the writer in recent papers [LEE, 1954 ab] are as follows

$$N = t^2 (s_y/\bar{y})^2 / (1 - \mu/\bar{y})^2 = t^2 v^2 / e^2$$

for normals;

$$N = t^2 (s_Y/bS_x)^2 / (1 - \beta/b)^2 = t^2 V^2 / e^2$$

for regression line, where t is the well known Student's value, μ and β are the true values of $\bar{y}$ and b, e is the desired accuracy in per cent of $\bar{y}$ or b, v and V are the coefficients of variation, and

$$s_y = \sqrt{\Sigma(y - \bar{y})^2 / (N - 1)}$$

the standard deviation of y

$$s_Y = \sqrt{\Sigma(\bar{y} - Y)^2 / (N - 2)}$$

the standard error of estimate from the line of regression

$$S_x = \sqrt{\Sigma(x - \bar{x})^2 / N}$$

the root-mean square deviation of x from its mean.

It is also interesting to note that, in Figures 2 and 5, the observed variance of ten- or five-year means about the 32-year normal may be represented by a regression line with confidence intervals written as

$$Y = a + b(1 \pm e)x$$

Theoretically, a should be zero and b = 1. This offers an explanation that 'the largest means show the greatest departures from the 45° line.' Suppose that the line is fitted with random means of three ten- or six five-year periods making up the 30 years and e is accordingly obtained, the equation established may be extended to use for any period of equal length. For example, if a regression line is established using the random period 1942-1946, it may be used to estimate the normal for a station having a record for any period, say 1943-1947.

If some relations between 30-year normals and the means of a certain period really exist, that is, they are grouped about the 45° line as indicated by the author, it seems that many problems arise and need further study. Is there a definite trend or some cyclic fluctuation of rainfall variations in the area under consideration? Are they significant in a statistical sense? It is believed that a thorough study will indicate the right approach.

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DISCUSSION OF

"THE APPLICATION OF THE RING INFILTROMETER TO DIAGNOSIS OF IRRIGATION PROBLEMS IN SOUTHERN CALIFORNIA"

by V. S. ARONOVICI

[Trans., v. 35, pp. 813-820, 1954]

Irving Sherman (13165 Welby Way, North Hollywood, California)--The paper is a valuable contribution to the study of infiltrometers and their uses. But some of the results presented are difficult for this writer to reconcile with the findings of a recent study, in which this writer had a part, made by the Los Angeles County Flood Control District. A brief summary of some of those findings and the methods used is presented below, in the hope that the author's closing discussion will explain some of the apparent differences.

The study by the Flood Control District [BROWN and SHERMAN, 1954] included an attempt to evaluate individual basins of the City of Sierra Madre's spreading ground by the use of infiltrometer tests. Early tests used a single-ring infiltrometer made from a steel barrel of 22-inch diameter. Surface heads were varied, the maximum being approximately 33 inches. Later tests used an inner ring within the 22-inch outer ring. Inner ring diameters of 6, 8.5, 10 and 12 inches were used.

The furrow infiltrometers apparently sometimes gave lower infiltration rates than the furrows, and the author's bufferred (double-ring) infiltrometer sometimes have higher rates than the unbufferred (single-ring) type. In the spreading ground tests, the single-ring apparatus indicated infiltration rates which were without exception far higher than those obtained in actual basin operation. The rates within the inner ring of the double-ring apparatus were always less than those of the single-ring; as the inner ring diameter was decreased, the infiltration rate from it also decreased, asymptotically approaching a limit of approximately half of the single-ring infiltration rate. Presumably this lower limit is a measure of the rate to be expected in actual basin operation, neglecting such other factors as sediment accumulation. It was concluded that the single-ring apparatus produced an unrepresentatively high proportion of lateral flow.

The author states that considerable variation in the surface head made little or no differnece in infiltration rates. The tests performed by the Flood Control District confirmed the finding of SCHIFF [1953] that the infiltration rate is approximately proportional to the surface head, at least in the first few hours of a test.

It is planned that the study described by the writer be repeated and extended with more elaborate apparatus which will enable obtaining more complete data.

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BROWN, W. E., and IRVING SHERMAN, Report on sedimentation and infiltration investigation, spreading grounds, Sierra Madre, California, report in files, Los Angeles County Flood Control Dist., June 18, 1954 (unpublished).

SCHIFF, LEONARD, The effects of surface head on infiltration rates based on the performance of ring infiltrometers and ponds, Trans. Amer. Geophys. Union, v. 34, pp. 257-266, 1953.

V. S. Aronovici (Agricultural Research Service, Soil and Water Conservation Branch, Pomona, California, Author's closure)--Sherman is dealing with relatively large basins where field conditions differ markedly from isolated irrigation furrows. In the study of irrigation furrows, initial soil moisture is usually low and duration of infiltration runs are short. The main driving force in moving water into the soil is the head produced by the capillary gradient between the ring and the wetting fromt of the soil. Under such conditions the influence of head of water on the surface of the soil is not directly proportional to infiltration velocities. Under conditions of long-term infiltrometer runs or high initial soil moisture or both, the capillary gradient within the soil is low. Under these conditions the head of water on the soil surface would be directly related to infiltration velocity.

The results, as presented in the subject paper, do clearly indicate that infiltration velocities within buffered rings are consistently lower than unbuffered rings. The Hamilton furrow infiltrometer can not be compared with the conventional ring infiltrometer because it is open on the furrow sides.

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REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

TARDI, PIERRE, and GEORGES LACLAVÈRE, Traité de Géodésie, Tome II: Astronomie Géodésique de Position, Gauthier-Villars, Paris, XIII + 366 pp., 1955.

This second volume of Traité de Géodésie, devoted to geodetic astronomy, fills a definite void in the modern literature. In recent years we have had such works as those of Roelofs and of Nassau in English, and of Niethammer in German, but none of these was intended to give definitive coverage of a field in which the variations from classical practice are too often concealed in dry statistical reports and tabulations.

Tardi and Laclavère have striven to provide concise developments of the theory fundamental to geodetic astronomy without skimping and yet without becoming overspecialized. Thus the section on astronomic refraction deals intensively with the theory for refraction over the range of zenith distance suitable for precise work but does not become mired in the more complex analysis required near the horizon where the conventional series expansion fails to converge. Perhaps the twenty pages or so on precession and nutation are too condensed, yet enough is given so that the significance of the quantity $(C - A)/C$ in one of the many overlapping problems of astronomy and geodesy is clear. Additional material on this area will no doubt be included in the treatment of latitude variation promised for Tome III. Another commendable inclusion is the discussion of the recent results showing the variability of the Earth's rate of rotation, and the subsequent adoption of 'Ephemeris Time' for certain purposes.

After what may be called the 'theory' come sections on the radio propagation of time, modern time keepers (including the 'atomic' clock), methods of establishing the instant of observation (by chronograph, by coincidence, and by extinction), and a discussion of personal equation, its measurement and its elimination.

Because the authors feel that the conventional meridian methods of astronomy are overworked in geodesy, having been taken over from fixed observatories with only peripheral modification, they provide an excellent chapter on equal-altitude methods, instruments, and the related techniques of computation.

Although they are convinced of the superiority of determining time and latitude simultaneously, they have not failed to include a valuable chapter on the classical meridian methods. Here one finds certain particulars, for example, of the method used in France to evaluate lost motion in the micrometer screw, and a reference on page 304 to a device developed there for improving on the reading of the Horrebow-Talcott levels in precise latitude work. Here one finds also a detailed description of the new transit instrument designed by A. Danjon of the Paris Observatory.

The final chapter presents a group of miscellaneous methods for position determination which are either very rapid, or suitable for ordinary theodolites, or of some other special interest. Notable among these is the azimuth method proposed by A. Gougenheim and which has been advocated also by Canadian geodesists for work in high latitudes.

Since it is usual to conclude a review with some criticism, it is noted that the paper binding, judging from the review copy, is not very durable; that a Table of Contents, even though explicit, is not an adequate substitute for an index; and that a bibliography would have been a welcome and valuable addition.

ALFRED D. SOLLINS

EVE, A. S., and D. A. KEYES, Applied Geophysics in the Searth for Minerals, 4th ed., Cambridge Univ. Press, x + 382 pp., 1954, $7.50.

This new edition of the book on applied geophysics is a revision by Keyes of the original version which first appeared in 1928. It was among the first texts to appear on the subject of prospecting using geophysical methods, and has been used as an introductory text book at McGill University for more than twenty years. As the title indicates, the main emphasis of the book is upon instrumentation, application, methods, and interpretation as related to prospecting for ores and minerals. The book is designed for beginners in the field and makes no pretense of being a source book.

The approach to the subject matter of geophysics in this book is logical, and it contains material on methods and techniques not found elsewhere. The author's presentation indicates a first-hand knowledge of the subject as well as indicating a lively interest.

Ten chapters and four appendices constitute the book. In them, the main divisions of geophysical prospecting are treated: magnetic, including airborne and ground; electrical; electromagnetic; gravitational; seismic; radioactive, including surface and in-hole; well-logging; and miscellaneous related methods and applications, which include paleontology, dipmeter, buried treasure locators, underground pipe location, diamond drilling, salt domes, and geophysical exploration in Australia.

There is contained new material on aeromagnetic methods and instruments, Lundberg's airborne electromagnetic method, gravimeters and gravimeter surveys, and seismic reflection equipment and surveys. There are 160 figures showing equipment, instruments, circuit diagrams, and results from field measurements. There are more than 225 references to articles and books included. These are largely representative of the basic information of geophysics and relatively few references are made to more recent work. Omission is noted of a number of important references to basic geophysical material, one, it is modestly mentioned, being the Handbook of Physical Constants, 1942, Special Paper 36 of the Geological Society of America, edited by F. Birch, J. F. Schairer, and H. C. Spicer.

A few errors are noted, though minor, in the new part of the book such as: page 294, 1,000 volts is meant for 100 in describing the plateau of a geiger counter; page 300, reference is made to Figure 138 where it should have been 139; page 302, reference to 'A' of Figure 141 is made but 'A' is not on the figure.

The book is an outstanding contribution and will be well received by those desiring an understanding of the fundamentals of exploration geophysics, and it will be most appreciated by the non-mathematical reader for the clear and precise unfolding of an inherently complex and difficult subject whose principles are founded upon higher mathematics.

H. CECIL SPICER

FAUL, HENRY (ed.), Nuclear Geology, John Wiley and Sons, and Chapman and Hall xvii + 414 pp., 1954, $7.00.

Nuclear Geology was planned as a well-rounded treatment of the subject, but less than half of the experts who were invited to contribute had supplied manuscripts when the book went to press. It is unfortunate that publication was not delayed until some of the gaps could be filled in.

The result is a book that gives an adequate treatment, for its purpose, of the theory and techniques of nuclear geology, but which is very sketchy on geologic data and interpretations apart from the occurrence and effects of some of the radioactive elements and a thorough discussion of absolute age determinations. The final chapter on the Origin of the Earth appears to have been an afterthought. One wonders why it was included in a treatise of this kind, since nuclear or isotopic phenomena are mentioned only incidentally in one paragraph.

The book can be recommended to geophysicists and geologists as an authoritative and concise treatise on the theory and techniques of nuclear (isotope) geology, with the most up-to-date summary of absolute age determinations extant. Even in theory and techniques, however, the use of radioactive tracers in geologic problems is conspicuous by its absence and fractionation of stable isotopes in nature receives no systematic treatment.

EARL INGERSON

ADAMS, FRANK DAWSON, The Birth and Development of the Geological Sciences, Dover Publications, New York, v + 506 pp., 1954; clothbound, $3.95; paper bound, $1.95.

This very informative history of the Earth sciences is an unabridged reissue of the first edition which was published in 1938.

The chapters of the book are organized to give the reader an interesting resumé of the early beliefs regarding the origin of stones, gems, minerals, fossils, mountains, volcanoes, springs, and rivers which attracted the attention of the ancient writers. One of the chapters is devoted to the early Grecian and Roman writings, which included incidental reference to the belief in a central fire within the Earth, the alteration of relative positions of land and water, and the remains of animals and plants enclosed in the rocks. The book traces the history of geologic thinking from these early writers to the first half of the Nineteenth Century when the geological sciences began to develop and geology received world-wide recognition and economic application.

Especial attention is given the contributions to the field of geology by such prominent leaders as Agricola, who is considered to be the father of mineralogy; Werner, who is credited with elevating geology to the rank of a real science; Lyell, whose Principles of Geology gave the death blow to the catastrophic school of geologists; William 'Strata' Smith, the father of English geology and stratigraphy; Hutton, the father of historical geology; and Maclure, the father of American geology.

Ninety-one illustrations, including portraits of some of the early leaders, and diagrams showing attempted explanations for the origin of artesian wells, volcanoes, mountains, and other geologic phenomena provide additional interest for the reader. Brief excerpts from many of the early writings are liberally interspersed throughout the fourteen chapters comprising this authoritative book.

In addition to the historical background provided for those interested in the Earth sciences, the book is particularly recommended as a supplementary reference text for courses on the History of Geology and for references to the early contributions in certain specialized fields of geology.

GEORGE V. COHEE

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NOTES AND PERSONALIA

NOTES

Additional postdoctoral awards to be made by National Science Foundation--The National Science Foundation has announced that a second group of postdoctoral fellowships will be awarded October 20, 1955, on the basis of applications received through September 12, 1955. Interested persons should write to the Fellowship Office, National Research Council, 2101 Constitution Avenue, N. W., Washington 25, D. C.

Symposium on Geochemistry at Minneapolis, Minnesota--A Symposium on Geochemistry under the auspices of the Division of Physical and Inorganic Chemistry of the American Chemical Society is to be held at Minneapolis, Minnesota, September 12, 1955. Eighteen papers are scheduled to cover a wide range of subjects for this one-day Symposium. The afternoon session will be devoted to the geochemistry of uranium and nuclear geology. Interested persons should write to the Presiding Chairman, Farrington Daniels, Department of Chemistry, University of Wisconsin, Madison, Wisconsin.

Alfred P. Sloan Foundation fund for basic research in physical sciences--The Alfred P. Sloan Foundation has established a $5,000,000 fund to promote basic research in the physical sciences. The program is expected to be in operation late in 1956 and will determine areas where there seem to be extraordinary needs and opportunity for fundamental advance, and will seek scientists to work in these fields.

Bell Telephone Laboratories fellowship program on electric communications--The Bell Telephone Laboratories has established a fellowship program for students doing research work in electric communications. Recipients will not necessarily limit their study to electrical engineering but to any aspect of the fields of geophysics, mathematics, chemistry, and so on, that may aid in the solution of electric communications problems.

Eighth Expedition of the Juneau Ice Field Research Project--The Juneau Ice Field Research Project is continuing this summer under the auspices of the American Geographical Society which is making detailed studies of Lemon Creek Glacier, as well as observations on other glaciers in southeastern Alaska, in an effort to add to our knowledge of the relationship between weather and glacier behavior. The first seismic soundings to be taken of Lemon Creek Glacier will be made this season. This Glacier is about four miles long and one mile wide, and is one of the possible sites for observation during the International Geophysical Year, 1957-58. Edward R. LaChappelle is the field leader.

National Science Foundation report on scientific manpower shortages--A report entitled 'Shortages of scientists and engineers in industrial research' has been prepared for the National Science Foundation by the Bureau of Labor Statistics of the Department of Labor. Copies of this may be secured by requesting Scientific Manpower Bulletin 6 from the National Science Foundation, Washington 25, D. C.

Continuation of fellowship program of the Shell Companies Foundation--This program, which is a combined program of awarding of fellowships plus support of institutions for use in carrying on research, is being continued for the school year 1955-56. Under the program 49 fellowships will be made available to 36 institutions for graduate education in various fields including geophysics in its various phases. Each fellowship will have a stipend of $1500 (which will be awarded by the school to which the grant has been made) plus tuition and fees, and provides supplements for equipment and facilities up to $500. The total fellowship award for 1955-56 will be $125,000, which with the grants to institutions will total about $350,000.

Astrophysical research activities of Harvard University and Smithsonian Institution to be integrated--It has been announced that Fred L. Whipple, Director of Harvard College Observatory, will become Director of the Astrophysical Observatory of the Smithsonian Institution. The headquarters of the Smithsonian Astrophysical Observatory will be moved to Cambridge, Massachusetts, in order that astronomers may work in close association with the program of solar research at Harvard University. Whipple will continue to serve as Professor of Astronomy at Harvard, and it is contemplated that there will be other joint appointments by the two institutions. The Astrophysical Observatory will continue its activity in the Solar Associates Group which serves as a coordinating body in connection with work at the High Altitude Observatory at Climax, Colorado, the Upper Air Research Observatory of the Air Force at Sunspot, New Mexico, and the Central Radio Propagation Laboratory of the National Bureau of Standards at Boulder, Colorado.

Fourth National Clay Minerals Conference to be held at Pennsylvania State University, October 10-13, 1955--This Conference will be held at Pennsylvania State University, University Park, Pennsylvania, over the four-day period October 10-13, 1955, under the sponsorship of the Clay Minerals Committee of the National Research Council. Field and Laboratory trips will be made on October 10, and the other three days will be devoted to the presentation of papers. Interested persons should get in touch with the Secretary of the Clay Minerals Committee, A. F. Frederickson, Stanolind Oil and Gas Company, Stanolind Building, Tulsa, Oklahoma.

World Symposium on Applied Solar Energy--As noted earlier, this Symposium will be held under the joint sponsorship of the Stanford Research Institute and the University of Arizona at Phoenix, Arizona, November 1-5, 1955. A tentative program is now established and the final details are being worked out. In addition to the general program, there will be work sessions of technical programs which will permit discussions in detail of specific phases of solar energy and offer opportunity for the presentation of volunteer papers. Anyone desiring to submit such a paper for consideration should communicate with Dan MacLachlan, Stanford Research Institute, California.

New river stations on the Yangtze in China--A substantial number of new river gaging stations have been installed in the Yangtze Basin this year to add to the hundreds already in operation. The new stations are in the headwaters, including tributary Han River, and have been installed to improve forecasting of flood stages in the lower river. River stages and rainfall amounts will be reported promptly to the central flood-control headquarters.

New graduate assistantship at Texas A and M College--It has been announced by the Department of Oceanography of Texas A and M College that a new graduate assistantship established by A. H. Glenn and Associates has been made available to the College for a suitably qualified student with a baccalaureate degree, for work in meteorology, physical oceanography, or some related aspect of science. Applicants should send word to the Department of Oceanography, Texas A and M College, College Station, Texas.

Ninth General Assembly and Eighteenth International Geographical Congress--As noted earlier, this Assembly and Congress will take place in Rio de Janeiro, August 9-18, 1956. The first circular outlining the agenda and the program is now available. Persons who are interested should send their inquiries to Secretaria Executiva da Comissão Organizadora do XVIII Congresso Internacional de Geografia, Av. Presidente Antônio Carlos, 40-9.° andar, Rio de Janeiro, Brazil.

New meteorological publication--A new publication entitled Weather Research, which is perhaps the only monthly magazine dealing exclusively with weather forecasts, is being issued by the Blewett Weather Service of Los Gatos, California. It is concerned solely with weather forecasts and changes in weather and their effects for the main weather areas of the United States, with special emphasis on the Western States. S. E. Blewett, the Editor, has specialized in weather forecasting since 1938, and during World War II was in charge of meteorological research and long-range weather forecasting for military services at the California Institute of Technology.

PERSONALIA

Detlev W. Bronk, President of the National Academy of Sciences and Director of the Rockefeller Institute for Medical Research, was recently awarded an honorary Doctor of Science by Yale University

Sydney Chapman, English geophysicist, Emeritus Professor of Oxford University, Professor of Geophysics of the University of Alaska, and Chairman of the International Committee for the International Geophysical Year, has begun a year's appointment for work at the High Altitude Observatory of the University of Colorado.

J. Cl. de Bremaecker, geophysicist with the Institut pour la Recherche Scientifique en Afrique Centrale, Belgian Congo, is on leave from his work for a year which he will devote to study at Lamont Geological Observatory on a Boese postdoctoral fellowship. George H. Sutton of the Lamont Geological Observatory will take over his duties in the Belgian Congo during his absence.

Philip C. Doran, Captain, U. S. Coast and Geodetic Survey, has been named the new Chief of the Division of Geodesy of the Survey.

W. Maurice Ewing, Vice President of the American Geophysical Union and Director of the Lamont Geological Observatory of Columbia University, has been given the Navy's Distinguished Public Service Award for his outstanding contributions to the United States Navy in his vigorous pursuit of understanding of marine phenomena.

Norman J. Holter, Research Director of the Holter Research Foundation, Helena, Montana, has been named President Elect of the Society of Nuclear Medicine.

Albert J Hoskinson, President of the Section of Geodesy, AGU, and Captain and Chief of the Division of Geodesy of the U. S. Coast and Geodetic Survey, retired July 1, 1955, after more than 34 years of service with the Survey.

Joe Webb Peoples, Professor of Geology at Wesleyan University, Middletown, Connecticut, is on a two-year leave of absence for a study of the chromite resources of the Philippine Islands for the U. S. Geological Survey.

W. Armstrong Price has retired from his post as Professor of Geology, teaching of geological oceanography and Pleistocene geology, at the Texas A and M College but continued work at the College through the past year on research on coastal geology for the Office of Naval Research. He has now returned to Corpus Christi, Texas, to enter the oil business as an independent oil geologist and operator.

Norris W. Rakestraw of Scripps Institution of Oceanography, who has served as Editor of the Journal of Chemical Education for the last 15 years, will retire from these activities on September 1 in order to be able to devote more time to research.

Leslie G. Smith, English geophysicist working with the U. S. Air Force Cambridge Research Center, has been awarded the 1954 Darton prize of the Royal Meteorological Society of London for his paper entitled 'An electric field meter of extended frequency range.'

R. F. A. Studds, Rear Admiral and Director of the U. S. Coast and Geodetic Survey, retired at the end of July, 1955, after about 37 years of service with the Survey.

Harold C. Urey, Professor of the Institute for Nuclear Studies of the University of Chicago, was recently awarded an honorary degree of Doctor of Laws by the University of California.

Felix A. Vening Meinesz, Dutch geophysicist and formerly Director in Chief of the Royal Netherlands Meteorological Institute, has been awarded an honorary Doctor of Science by Columbia University. Especially cited was his work on the measurement of the variation of the value of gravity which has made possible the accurate calculation of the size and shape of the Earth.

Theodore von Karman, Director of the Guggenheim Aeronautical Laboratory of the California Institute of Technology, has been named as one of the 14 new appointees to the Pontifical Academy of Science. The total number of academicians is now 66.

Gilbert F. White, President of Haverford College, has resigned to become Professor of Geography at the University of Chicago.

Vsevold L. Skitsky, Librarian with the U. S. Geological Survey, working largely on the Bibliography of North American Geology, died March 12, 1955, at the age of 61. He was born at Romny, Russia. In 1916 he graduated from the Imperial Institute of Ways and Communications. In the earl 20's, he came to the United States, took his master's degree at Columbia University in 1926, and his doctorate from the University of Michigan in 1940. His knowledge of scientific Russian and as a scientist made his translating ability especially valuable. From 1943 to 1948, he served as edito of Geological Abstracts, published by the U. S. Geological Survey. He became a citizen of the United States in 1928 and a member of AGU in 1949.

Victor Cyril Stechschulte, Head of the Department of Physics and Director of the Seismological Laboratory of Xavier University in Cincinnati, died March 3, 1955, at the age of 61. He was born at Leipsic, Ohio, and entered the Order of the Society of Jesus at St. Stanislaus Seminary at Florissant, Mo., in 1912. He pursued his studies and teaching, took his baccalaureate degree in 1919 from St. Louis University, and his master's degree from the same school in 1920. He took his doctorate from the University of California in 1932, when he entered upon his duties at Xavier University. He served as Vice-President of the Section of Seismology from 1941 to 1944 and as President from 1944 to 1947. He had been a member of AGU since 1932.

Carl Fred Giffey, hydraulic engineer for the Corps of Engineers, U. S. Army, died March 14, 1954. He was born at Lone Tree, Iowa, in 1902. He attended Iowa State College. In 1941 he entere the service of the Corps of Engineers with whom he worked through his entire professional career. He had been a member of AGU since 1945.

George Hartnell, formerly Observer-in-Charge of the Cheltenham Magnetic Observatory, died in Wyoming, New York, on May 20, 1955, at the age of 84. He was born in Bergen, New York. The early part of his professional career was devoted to high school teaching. He subsequently became a lens grinder for the Gundlach Optical Company and Director of the Optical Lens Shop of Queen and Company in Philadelphia. In 1908 he entered the service of the U. S. Coast and Geodetic Surve and was initially assigned to the Vieques Magnetic Observatory in Puerto Rico. In 1911 he was designated Director at the Cheltenham Magnetic Observatory, Maryland, where he continued until his retirement in 1941. He had been a member of AGU since 1930.

John Putnam Marble, General Secretary of the American Geophysical Union, died suddenly on June 6, 1955. A brief biography appears on the opening pages of this issue.

Harry M. Ryder, consulting engineer and geophysicist, died July 6, 1954, at the age of 63. He was born at Lancaster, Pennsylvania, took his baccalaureate degree in Pennsylvania State College in 1911 and his master's degree in physics in 1916. His early work was on field and laboratory investigations of the fluid content of oil sands and the mechanics of retention and movement of heterogeneous fluids in and through oil sands, including investigations of detailed stratigraphy in oil-bearing formations. He had been a member of AGU since 1946.

Transactions, American Geophysical Union Volume 36, Number 4 August 1955

MINUTES OF EXECUTIVE COMMITTEE MEETING, AMERICAN GEOPHYSICAL UNION

First Session, May 1, 1955

The meeting was called to order at 14h 09m in the Board Room of the National Academy of Sciences - National Research Council Building, 2101 Constitution Avenue, Washington, D. C., by President James B. Macelwane.

Present--Thirty-four persons were present, namely: L. H. Adams, John M. Adkins, L. R. Alldredge, W. W. Atwood, Jr., K. Hilding Beij, L. V. Berkner, Francis Birch, Harry F. Blaney, James J. Capello, Felix Chayes, Phil E. Church, E. A. Eckhardt, Maurice Ewing, William F. Foshag, Ross Gunn, Ross R. Heinrich, Harry H. Hess, Albert J Hoskinson, Woodrow C. Jacobs, J. W. Joyce, Joseph Kaplan, H. E. Landsberg, Walter B. Langbein, John Lyman, James B. Macelwane, John Putnam Marble, Jerome Namias, James A. Peoples, Jr., Donald W. Pritchard, Richard J. Russell, Waldo E. Smith, Harlan T. Stetson, Harold G. Wilm, and James T. Wilson. The following were excused: Hugo Benioff, R. R. Bodle, Perry Byerly, H. R. Byers, Jno. A. Fleming, W. E. Hiatt, Ben Holzman, Harry S. Ladd, Esper S. Larsen, Jr., Ray K. Linsley, G. A. Macdonald, Brian O'Brien, A. C. Redfield, A. N. Sayre, M. O. Schmidt, Louis B. Slichter, V. Vacquier, and Paul Weiss.

Approval of minutes--The minutes of the Executive Committee meeting on December 4, 1954, published in the February, 1955, issue of the Transactions (pp. 156-168), were approved.

General Secretary's Report

This is essentially a factual report of matters attended to during the past approximately six months.

Transactions and other publications--The following issues have been printed and distributed since the last meeting:

December 1954, Part 1 -	158 numbered pages (unnumbered title page and obverse, blank) being papers.
Part 2 -	130 numbered pages (2 unnumbered pages) being Directory.
February 1955	190 numbered pages, (2 unnumbered pages) edition of 6200.
April 1955	192 numbered pages, edition of 6200

Program for Annual Meeting - 48 pages.

The Editorial and Publication Committee decided not to include the entire program in the Transactions, but has placed proofread abstracts of the papers in the June issue, with other abstracts and reviews. Section Secretaries have included other portions of the program as they saw fit in the Section minutes. This avoids loading what is properly a journal of research with purely administrative matters of little permanent interest.

Number of manuscripts in process beyond next issue in each case:

	April 27, 1955	Sept. 3, 1954	May 6, 1954
Ready for publication	7	23	23
With editors	41	59	48
Others	11	10	6
Totals	59	92	81

Not considering the June issue, at this time we have approximately 20 papers which, if all goes normally will be delayed over 6 months in publication from the date when received in the Union office. A year ago this figure was approximately 35. Papers in authors' hands are not counted. Thus some progress has been made in fulfilling the mandate of the Executive Committee that publication should normally average not more than six months.

As you know, we have received a grant of $4,000.00 from the National Science Foundation to help us catch up to this schedule. In the February issue 30 additional pages over our budgeted normal were printed, and 32 pages in the April issue; total 62 pages at about $25 per page is $1,550.00. At this rate the grant will be used up by the time the October, 1955 issue is printed. In the budget estimates, half of the total grant was assumed to be available during the next fiscal year.

Due to increases in membership and to increased demands from libraries and other sources for back issues, our stock thereof is not as great as it should be. Every time we increase our printing run the demand increases still more. A list of available back numbers is available for those interested. We are in touch with a reprint organization who wish to reprint our out-of-print issues.

Matters connected with revised format of and advertising in the Transactions are progressing, and definite arrangements will be announced in due course.

Membership--Data are:

Membership, December 1, 1954	5070	
Reactivated	2	
New Members, December 1, 1954 to April 27, 1955 including 9 applications in process	132	5204
Resigned	125	
Inactive	1	
Deceased	8	134
Membership as of April 27, 1955		5070

The following deaths have been reported to the Union office since our last meeting: Oliver C. Lester, Sr., Sept. 28, 1951; Bernard A. Etcheverry, October 26, 1954; John C. Beebe, Dec. 13, 1954; Joseph B. Kincer, Dec. 14, 1954; John R. Kinney, Dec. 28, 1954; Robert Balk, February 19, 1955; Victor Cyril Stechschulte, March 3, 1955; and Vsevold L. Skitsky, March 12, 1955. Dr. Lester was a life member, and, as in some other recent cases, we were not notified of his decease for several years, as no bills for dues were in order.

Dues unpaid--	Owe for 1955	1014
	Owe for 1/2 of 1955	50
	Owe for 1954 and 1955	245
	Owe for 1/2 of 1954 and for 1955	6
	Owe for 1953, 1954, and 1955	140
	Owe for 1/2 of 1953, for 1954, and for 1955	17

It is required that the 157 who have not paid their dues for 1953 and subsequent years be reported with the recommendation that they be dropped from membership. As is customary, the further recommendation is made that the office be instructed to make an additional effort to get them to return to good standing. In previous years, this effort has been quite successful.

Finances--Below is a brief statement of our assets as of April 1, with comparison for the last two years.

	April 1, 1955	April 1, 1954	April 1, 1953
Cash balance	$24,459	$21,742	$20,919
Permanent Fund	11,573*	8,000*	6,398*
Emergency Fund	1,080	1,043	1,028
T. M. and E. Award Fund	465	210	....
Totals	$37,577	$30,995	$28,345

*Does not include interest on $2,368 of U. S. Savings Bonds.

Detailed figures for the past year are available for inspection. See also report of the Budget Committee, Appendix 1, herewith.

Office staff and jobs--Jas. J. Capello, Assistant to Executive Secretary and Assistant Editor; Glenda Quinn, Clerk-Stenographer; Elsa M. Sarmiento, Clerk-Typist; Milena Vaneckova, Clerk-Typist; Zdenka Dalecka, Electromatic Operator and Assistant to the Editor; David Miller, part-time Office Boy; all under the direction of Waldo E. Smith, Executive Secretary.

Status of Air Force Contract--The Conference called for under this non-budgetary item was held in Portsmouth, N. H., in May 1954, and was apparently successful. All papers have been received and are undergoing editorial processing. About 1/3 are completed, and some have been set up in the Union office for offset printing. There will be about $5000 left of the appropriation, and plans are under way to extend the contract ten months beyond last April 30, and hold a conference, purely domestic, on the physics of cloud and precipitation particles. This is expected to be held at Woods Hole on Sept. 7-10, with no travel expenses paid to participants, and the submission of a fully edited manuscript ready to be set up, fulfilling the part of the Union as regards publication. If additional funds become available, we may set up the master copy.

Status of Bibliography of Hydrology--Work on this contract, made with the U. S. Bureau of Reclamation, to cover the United States and Canada for 1951-1954 is well under way. Ray K. Linsley, who is doing the work, reports compilation 75 pct complete, we should complete the master copy by November 1, 1955, the termination date.

International Matters--No further word has been received as to the next meeting of IUGG, scheduled for Buenos Aires in 1957. No formal publications of the Rome papers by any of the Associations have yet come to hand. [Plans are under way to change the status of the IUGG News Letter from one sent without charge to a limited number of official recipients, to a subscription list at the rate of $8.50 per year, issued on a quarterly basis.]

Matters relating to the Union and its affairs--The results of the ballot last January on revision of the Statutes and By-Laws of the Union resulted in an overwhelming favorable majority as reported by the Committee of Tellers [see April, 1955, p. 374]. A full statement of the Statutes and By-Laws, as revised, will be printed in the *Transactions* [see June 1955, pp. 564-568]. Action recommended to be taken by the Executive Committee in this connection will be submitted subsequently.

We have the following representatives on other NRC groups:

Division of Earth Sciences: Harry H. Hess
Division of Physical Sciences: Walter H. Bucher
U. S. National Committee on International Geophysical Year: J. P. Marble, in his capacity as General Secretary
Board of Directors, American Geological Institute: E. A. Eckhardt, H. R. Joesting

A number of other active members of AGU likewise serve on the U. S. National Committee as individuals who serve because of special qualifications.

The following are NRC representatives in the Union:

Chairman, NRC - none currently designated; Dr. Bronk and Dr. Cornell are invited to attend our meetings.
Chairman, Division of Earth Sciences - Richard J. Russell
Chairman, Division of Physical Sciences - Brian O'Brien
Chairman, Division of Chemistry and Chemical Technology - William J. Sparks
Chairman, Division of Biology and Agriculture - Paul A. Weiss
Director, Office of International Relations - Wallace W. Atwood, Jr.

Our representatives on the Council of the AAAS are J. P. Marble and L. B. Slichter.

Special Delegates--Everly J. Workman was our representative to the Symposium on Arid Lands recently held in New Mexico under AAAS auspices. He is one of the leaders of the local groups. Daniel Linehan, represented us at the inauguration of Arthur B. Brownell as President of Worcester Polytechnic Institute in Worcester, Mass., on April 30, 1955.

The Executive Secretary attended a meeting of the business officers of the AGI affiliates in New York on March 25, and plans to attend a similar meeting of the Council of Engineering Societies Secretaries in Philadelphia on May 24 and 25. The General Secretary attended a meeting of the AGI Committee on Government Relations in New York on March 28.

Regional Meetings--The newly organized Pacific Northwest Regional Committee organized a meeting at Portland, Oregon, on December 4, 1954. The Pacific Southwest Regional Committee held its annual meeting at Berkeley, California on February 4-5, 1955, with about 200 in attendance.

Quarters--We have completed arrangements with the Carnegie Institution of Washington to occupy our present office space through January, 1956, at least.

Committees--The revised statutes and by-laws have added Lloyd V. Berkner, Chairman of Committee on International Relations and Wallace W. Atwood, Jr., Director of the Office of International Relations to our Executive Committee as regular members.

Walter H. Bucher was named Chairman of the Committee on Nominations, but relinquished the job as he is to be in Europe for several months, and Helmut E. Landsberg, who replaces him, joins our group.

Robert Balk, member of the Executive Committee, was killed on February 19, 1955, in an airplane accident. The Statutes provide that the last Past President of a Section shall be a member of the Executive Committee, and as Balk was the last Past President of Tectonophysics, he was a member. If the Statutes indicated that the last living Past President is a member of the Executive Committee, we would have had a replacement. The question whether our Statutes should be so interpreted should be discussed.

In conclusion, your General Secretary thanks all of you, who have held up his hand during the past months. He is especially grateful to our hard-working and effective Executive Secretary for loyal support and a multitude of jobs well-done.

John Putnam Marble
General Secretary

Action on the General Secretary's report--The report was accepted.

Action on recommendations by the General Secretary--The recommendations of the General Secretary with respect to members who had not paid dues from 1953 to 1955 were approved, namely, that one more attempt be made to return these persons to active membership, following which those who do not respond will be dropped.

Comments by the President--President Macelwane expressed thanks to the members of the Union as a whole for the confidence and cooperation that was shown as indicated by the results of the recent ballot on the amendments to the Statutes and By-Laws. He felt that this action will be looked back upon as a milestone in the history of the Union.

Reports of Standing Committees

International Participation--Chairman Berkner pointed out that the President appointed this Committee formally at the time of the last meeting of the Executive Committee on December 4, 1954. The Committee has held one meeting, and has set up an agenda and divided its work among working groups which are to bring in separate reports. (The Committee held its second meeting on May 1, 1955, following the meeting of the Executive Committee.) It was anticipated that the Committee would go thoroughly into its responsibilities and within a year be able to bring to the Executive Committee a full report on the various aspects of the international problems in order that the Executive Committee may have basis for making a number of important decisions with respect to its relations with the International Union of Geodesy and Geophysics and its international problems in connection with the National Research Council. President Macelwane pointed out that on the previous day a seven-page letter had been received from General Secretary Laclavere of IUGG which was being referred to the Committee on International Participation.

W. W. Atwood, Jr., Director of the Office of International Relations of NAS-NRC, pointed out that the bureau of ICSU met in Washington the first part of March, 1955, and problems of ICSU were discussed at length with the U. S. Committee on International Union and several decisions were made with respect to the position of our delegation to the Oslo General Assembly of ICSU in the coming summer. It was felt, among other things, that the national dues to ICSU should be substantially increased. Berkner and Bucher will attend the ICSU meeting at Oslo and will be in a position to represent the interests of the United States as well as those of IUGG. Other delegates from the United States will include W. W. Atwood, Jr., and Paul Weiss of our Executive Committee and C. E. Sunderlin of the National Science Foundation.

Atwood also mentioned matters pertaining to the publication and distribution of publications of IUGG and other Unions, pointing out that the distribution is not good and that it is quite difficult to find back copies of many items. IUGG is taking certain steps to clear up this difficulty which would take care of the problem in the future.

Various policy questions with respect to international science were also raised, such as the admission of new Unions to ICSU and of the structure of ICSU itself. The Australian Academy of Sciences has taken the position that ICSU should not have national members but rather only members from the constituent Unions. This is to be discussed at length at the Oslo meeting.

It was mentioned that at the Rome meeting of IUGG steps were taken (confirming action necessary at the next General Assembly) to set up a system of dues so that there will be 15 categories of membership instead of eight. (This is already being put into practical effect. The USSR, which recently joined, is in the 15-category group and France is in the ten-category group, while the United States remains in category 8.) Our own policy with regard to the 15-category plan should be established soon on recommendation of our new Committee on International Participation (CIP) as this involves the future finances of IUGG.

Atwood discussed the idea of the Federation of Permanent Services of IUGG and how these might be financed in the long run. With IUGG finances on a rather meager basis, there seemed no immediate solution to the problems within IUGG. UNESCO is being asked for further support.

There was also some discussion of the News Letter of IUGG which has been distributed since its inception in 1951 to a limited number of addresses in each member country without charge. It has been expanded and has taken in advertising and has become a sizable publication. The free distribution must be greatly curtailed as arrangements have been entered into with a commercial printer (Butterworth) to put this on a paying basis. Annual subscriptions will be $8.50 a year. The policy with regard to this was being referred to the Committee on International Participation.

International Geophysical Year--Joseph Kaplan, Chairman of the U. S. National Committee for the International Geophysical Year, outlined recent developments and pointed out that J. Wallace Joyce's appointment as head of the IGY office of the National Science Foundation was a splendid move. He indicated that progress is being made with regard to securing the necessary funds from Congress and that hearings were currently being held. He pointed out that there are organizational problems, finance problems, and technical and scientific problems, and that the whole program is rounding out very well and is very much bigger than anticipated two years ago. He mentioned the recent addition of gravity and seismology to the work to be undertaken, indicating that these fields are now represented by well-prepared programs under the guidance of Panel Chairman Macelwane. He mentioned the anticipated symposium which AGU will sponsor in connection with the AAAS meeting in Atlanta in December, 1955, and that there will be three morning sessions on the IGY. These will be programs designed for the general scientific public rather than for particular specialized fields.

L. V. Berkner, Vice Chairman of the ICSU Committee on the International Geophysical Year, mentioned that IGY is moving along very well, with the plenary sessions planned to be held in Brussels, September 7-15, 1955. He stated that the plenary sessions in Rome in October, 1954, had adopted a world program in final form. He also mentioned that the financial difficulty that existed up to early April had been alleviated substantially by a grant from UNESCO. He indicated that in excess of 40 nations, including the USSR, are taking part.

The Executive Secretary outlined the tentative plan that is being developed for a possible symposium on the Antarctic to be held in connection with our meeting in May, 1956, but plans in this regard are waiting formalization on the scope and magnitude of the symposium. At this time it is felt that this might either be a limited national symposium or one on which we would need to seek NSF aid as a rather broad conference. The President mentioned that the NSF strongly favors this type of conference.

Berkner mentioned that ten nations will participate in the Antarctic work and that 26 or 27 stations will be set up in that vicinity, with ten general stations on the Antarctic Continent itself.

He cited that a meeting is to be held in Paris in June in which all nations participating in the program will take part. A meteorological network of 50 to 60 stations is planned for the Antarctic, and there will be ice surface investigations in the hope of establishing the total ice content of the Continent much better than at present. Land operations will be supplied by air drops, and a team can go out with the expectation of support through such means.

With regard to conferences, President Macelwane mentioned that there seemed to be some thought that a conference on the shape of the Earth might be desirable. Kaplan mentioned that in connection with such conferences which are usually limited to a relatively small number of people, if these are held in centers of population it is a good idea to close the conference with a popular lecture open to the general public.

Editorial and Publication--Chairman Marble indicated that the essence of his report on this matter as it relates to operations completed appears in his report as General Secretary. He then called upon the Chairman of the Subcommittee on Advertising, John Lyman, who reported as follows:

An investigation was made with regard to whether the matter of advertising should be left in the office of the Union or be handled by an outside advertising representative. It was agreed that we should undertake the latter, and after extensive investigations, William A. James of New Haven, Connecticut, who now represents the American Scholar, the American Scientist, and the Yale Review, was selected, and arrangements were in their final stages of formalization. He pointed out that items in the budget relating to advertising are largely guesses only and were believed to be on the conservative side as far as receipts are concerned. He mentioned that a rate of $100 per page per issue had been established and that the estimated budget item of $5000 thus anticipated a total number of pages of advertising of about 50 for the next year, or an average of about eight or nine per issue. He felt that the return to the advertiser is more likely to be intangible rather than tangible. He enlisted the support of the Executive Committee in securing advertising, pointing out that a joint effort beyond the capabilities of a single firm or subcommittee is required. He distributed a sample letter that he felt might be a satisfactory appeal to prospective advertisers, and urged the Executive Committee members to send similar letters to any and every business executive of his acquaintance who might be in a position to place or influence the placing of advertising in the Transactions.

Chairman Marble then called upon Chairman Walter B. Langbein of the Subcommittee on Format, who presented the report set forth in Appendix 2. The Executive Committee expressed satisfaction with the progress being made, both in the fields of advertising and change in format. Chairman Marble pointed out that the improved format in publication should have greater appeal to potential advertisers.

Chairman Marble referred to the grant of $4000 received from the National Science Foundation to help us get caught up on our backlog. The estimate for this was based on a cost of $25 per page. Inasmuch as we published 62 additional pages through the April issue, we have used up over half of this grant and at this rate the grant as a whole will be used up with the October issue. However, for budgetary purposes one-half of the grant was placed in the fiscal year 1954 and the balance in 1955.

Both the President and the General Secretary spoke strongly in favor of the establishment in AGU as soon as possible of a series of monographs in addition to our Transactions which might be based on various conferences of which AGU is the sponsor. This idea received the general endorsement of the Executive Committee. In this connection, Berkner pointed out that according to the rules of the International Committee for the Geophysical Year (CSAGI) each country will be charged with responsibility of publishing its own data and analyses, that the U. S. National Committee will be faced with this problem, and that a series of monographs such as the AGU has here offered might well fit in with this program.

Statutes and By-Laws--Chairman Bodle of the Committee on Statutes and By-Laws and Chairman Ladd of the Special Committee on Tellers were both absent. Marble pointed out that the vote of the membership was overwhelmingly in favor of all the suggested changes in our Statutes and By-Laws [see April issue, p. 374], these changes giving the Executive Committee authority and the responsibility to set the dues rate for each year. It was voted that beginning as of January 1, 1956, the dues rate be $8.00. It was pointed out that it would be well to include a letter from the President or other officers of AGU explaining the changes in progress, what the members will receive for their increase in dues, and why the increase is necessary. The estimated budget calls for an increase in receipts of about $10,000 to take care of the change in format and to maintain a backlog of about six months.

Budget--Chairman Beij presented the budget as set forth in Appendix 1. The budget, with the report in full, was approved, including the report's recommendations. It was noted that one of these recommendations, namely, the requirement relative to years of membership to be eligible for life membership, is in the Statutes and cannot be modified except by action of the membership. While the recommendation is thus approved by the Executive Committee, it is referred to the Committee on Statutes and By-Laws for study and formal recommendation in order that this may ultimately be implemented. The approval of increases in rate of payment is the first step in the modification of this By-Law.

Meetings--Chairman Adkins reported that the Thirty-Seventh Annual Meeting will be held April 30 to May 2, 1956. He also reported that the Pacific Southwest Regional Committee held its annual meeting February 4-5, 1955, in Berkeley with about 200 present. The North Central Regional Committee will hold a meeting in Iowa City, June 16-17, 1955, following the close of the Hydraulics Conference being arranged by the Iowa Institute of Hydraulic Research. The Pacific Northwest Regional Committee is planning a meeting to be held in Portland, Oregon, November 18, 1955.

The Geophysical Society of Hawaii, which has recently become the Mid-Pacific Regional Branch of AGU, is affiliated directly with AGU and also with AMS; they are planning their first extended meeting November 15-17, 1955.

The *Ad Hoc* Committee appointed by the Southeastern Regional Committee plans to hold a meeting to consider organization in Atlanta, December 27-29, 1955. They are developing their own program, but in addition to this AGU will have an extensive symposium on the International Geophysical Year that will fit into the plans being developed by the Southeastern Regional Committee.

The Pacific Southwest Regional Committee will hold its annual meeting at the University of California at Los Angeles in late January or early February, 1956.

Chairman Adkins also reminded the President that we will expect a presidential address at the meeting in May, 1956.

Membership--In the absence of Chairman Hiatt, the Executive Secretary reported that the response to our general appeal to the membership to secure new members had been a disappointment, although it had been successful in yielding perhaps 100 or 150 new members that we otherwise might not have received. Considering the changes in prospect in the *Transactions* and with regard to the increase in dues, it was felt that a concerted campaign at this time is perhaps out of order but that we should continue in our regular way to secure new members wherever the opportunity offers.

Nominations--Chairman Landsberg noted that he had just taken over the chairmanship of this Committee and would welcome suggestions for nominees from members of the Executive Committee.

Reports of Special Committees

Cosmic-Terrestrial Relationships--Chairman Stetson summarized a report in hand that will be published in due course in the *Transactions*. The report was accepted.

Award of William Bowie Medal--Chairman L. H. Adams reported briefly that a recipient had been named and will be revealed at the evening session on May 3. (It is noted in the June issue of the *Transactions* that this was Walter H. Bucher.)

Award in Terrestrial Magnetism and Electricity--Chairman Gunn noted that collections for this fund had not been as rapid as he had hoped and that there is now a total of about $750 in the fund with about $3000 pledged to be paid as we approach our goal for this.

Corporation Memberships--Chairman Eckhardt indicated that this Committee had not been very active in the solicitation of new corporation memberships but that he has been getting in touch with many people to secure a background of information for the activity of the Committee. He felt that attempts to secure corporation memberships in AGU from corporations are not likely to be successful unless well planned and unless one can convince the corporations that this particular organization is deserving of support. He pointed out that time and care must be taken to prepare the proper approach.

Conference on Atmospheric Electricity--In the absence of Chairman Holzer, the General Secretary reported that the papers presented at this Conference are almost all in hand and are undergoing editorial processing, and that some work had been completed in setting these up in form for offset publication.

Reports of Sections

Volcanology, Geochemistry, and Petrology--President Foshag reported that the change in title of the Section seems to have worked to our advantage as reflected by the program for the annual meeting. He noted that a large number of the participants in the program are not now members of AGU and that in the case of 13 of the papers on the program, none of the participants is now a member of AGU. He felt that these were a good source of potential members that he planned to explore.

Affiliated Organizations

American Geological Institute--E. A. Eckhardt noted that he had written a letter to H. R. Joesting (these two being our representatives on the Board of the Institute) urging him to make the report but it was not possible for Joesting to be present. He also recalled that last October the AGU had sent to AGI a statement about the name of the Institute and relative to some of its activities, and that subsequently a committee was appointed to study these matters as follows: (1) To enumerate and classify the various professional groups represented in the member societies of AGI and to recommend which of them should be included within the scope of AGI so as to make AGI representative of a reasonably homogeneous professional population; (2) to recommend what professional groups, if any, not now represented in its member societies, should be included within the professional scope of AGI; (3) to consider the present and other appropriate names for AGI and to recommend one or more of them which seem to the committee to be best suited in view of the professional scope recommended by it; (4) to consider such other matters as may seem to the committee to be pertinent to items (1) to (3). At the meeting of the Institute in New York the committee made its final report, which was somewhat lengthy but the essence of which was as follows: The committee felt that it is undesirable to be specific regarding the professional groups which constitute AGI, that its present constitution is satisfactory, and that AGI not consider the inclusion of other groups at this time. The committee also felt that the present name of AGI was satisfactory and that diligent inquiry had indicated that there is dissatisfaction with this name only among a few people, and that, therefore, they recommended that the name not be changed. The Institute adopted this report.

American Association for the Advancement of Science--J. P. Marble (who with Louis B. Slichter are our members on the Council) noted that the AAAS had met at Berkeley at Christmas time and that several symposia and other sessions were jointly conducted under AGU and other auspices, although the AGU, as such, had no program. He indicated that the reports of the meeting had all been favorable.

National Research Council

Division of Earth Sciences--It was noted that Harry H. Hess has been appointed as AGU representative for another two-year term and is now Chairman Designate of the Division. Hess reported that one Ad Hoc Committee of the Division has been appointed to take care of the Vening Meinesz equipment to avoid the difficulties involved in loaning the equipment to an individual.

New Business

Recess--Recognizing the fact that there are likely to be further matters on which the Executive Committee should act during the annual meeting, it was voted to recess the meeting until immediately following the business meeting of the Union on Wednesday afternoon, May 4, 1955. The meeting recessed at 16h 33m.

Waldo E. Smith, Executive Secretary

Second Session, May 4, 1955

This second session was called to order at 15h 47m in the Auditorium of the NAS-NRC, 2101 Constitution Avenue, Washington, D. C., by President James B. Macelwane.

Present--Eighteen persons were present as follows: W. W. Atwood, Jr., Lloyd V. Berkner, Harry F. Blaney, James J. Capello, Phil E. Church, Maurice Ewing, Albert J Hoskinson, Woodrow

C. Jacobs, J. W. Joyce, Walter D. Lambert, James B. Macelwane, John Putnam Marble, James A. Peoples, Jr., Donald W. Pritchard, Milton O. Schmidt, Waldo E. Smith, David K. Todd, and George P. Woollard.

Only a few matters requiring attention developed during the Annual Meeting. A request has come in from the Mount Washington Observatory for the use of our mailing list on one occasion for circularizing our members with regard to the work of the Observatory. It was moved, seconded, and passed that the request of the Observatory be approved, with the understanding that the Observatory will be expected to pay the costs of this work.

The Committee on International Participation, meeting on the evening of May 1, 1955, made the suggestion that in order to quiet the statement of some people that AGU is nothing more than another scientific society, we should perhaps change the name of the annual financial contributions of members from 'dues' to 'annual contribution,' 'annual assessment,' or some such name. The suggestion was referred to the Committee on Statutes and By-Laws.

Adjournment--The meeting adjourned at 16h 03m.

Waldo E. Smith, Executive Secretary

APPENDIX 1--REPORT OF THE COMMITTEE ON BUDGET FOR THE FISCAL YEAR ENDING JUNE 30, 1956

K. Hilding Beij, Chairman

Herbert N. Eaton R. E. Gebhardt
John A. Fleming Henry W. Hemple

Your Committee, on the basis of information supplied by the General and Executive Secretaries, proposes the following Budget for the fiscal year ending June 30, 1956.

Self-liquidating contracts for the performance of work related to the interests of the Union are excluded from the Budget. According to needs, clerical assistance is engaged for work on such contracts. At present one such assistant is employed at a salary of $3000. Occasional work of regular employees on contracts is charged to the contracts. Five persons are now on the office staff. Salaries of two are set by the Executive Committee, and of the others are set by the General Secretary. At present these three positions are filled at entrance salaries of $2400. There is provision in the Budget for raises during the coming year. The item of $15,750 for salaries appears under General Office Expenses and the remainder is included under Transactions in the item Preparation, Printing, and Mailing.

In February, 1955, a grant of $4000 was received from the National Science Foundation for the purpose of reducing our backlog of papers awaiting publication so that the time from acceptance to publication might be reduced to about six months in the future. This is being accomplished by adding about 32 pages to each issue of the Transactions during 1955. Thus $2000 of the grant appears as income for the next fiscal year, and as an expenditure by an additional $2000 which has been included in the item for Preparation, Printing, and Mailing.

The coming change in format of the Transactions poses a question of costs which cannot be answered definitely at this time. The Executive Committee made tentative provisions for raising an additional income of $10,000. These provisions, all included in the Budget, are:

(1) Higher subscription rates--Counting on a normal annual increase in subscriptions, this should raise an additional $1500 next year.

(2) An increase in reprint prices--The additional revenue is expected to be about $2200.

(3) Display advertising in the Transactions--In the Budget an anticipated gross income of $5000 and an expenditure of $2500 have been included. However, the net return might be considerably more than $2500, and also it is quite possible that there might be a deficit during the first year.

(4) An increase in dues from $7 to $8--For the next year this will bring in about $3800 additional income, and in succeeding years about $4800, without taking into account any increase in membership.

Operating Statement

Estimated receipts:			
National Research Council grant		$ 400	
Income:			
Membership Dues		39,400	
Transactions:			
National Science Foundation grant	$ 2,000[a]		
Subscriptions	9,500		
Sales of reprints	4,600		
Gross advertising revenue	5,000	21,100	
Interest		400	
Miscellaneous		300	
Total receipts			$61,600
Estimated expenditures:			
Transactions:			
Preparation, printing, mailing	28,600		
Editors	1,500		
Direct advertising costs	2,500		
Cost of reprints	2,200	$34,800	
General office expenses:			
Salaries and Social Security	15,750		
Retirement contribution	1,000		
Stationery and supplies	1,000		
Postage and communications	1,500		
Equipment	500	19,750	
Expenses of Meetings:			
Annual	700		
Regional	200	900	
Expenses, Sections		100	
Expenses, Committees		200	
Travel of Officers		150	
Miscellaneous		100	
Transfer to Reserve for Directory		900	
Total expenditures			56,900
Estimated excess of receipts over expenditures			$ 4,700

[a] Second half of total grant of $4000.

Statement of assets as of June 30, 1955 and 1956 (both estimated)

		1955	Changes	1956
General Funds:				
Cash Reserve		$15,380	+$4,700 from Income	$20,080
Reserve for Directory		. . .	+ 900 from Income	900
Permanent Fund:				
U. S. Bonds at cost[a]	$2,368			
Northwestern Federal Savings and Loan Association	$9,205	11,573	None	11,573
Emergency Fund:				
Prudential Building Association[b]		1,080	None	1,080
Robert E. Horton Fund[c]		1,180	None	1,180
T. M. and E. Award Fund:				
Liberty Building and Loan Association		465	None	465
Bills receivable less bills payable		2,500	None	2,500
Totals		$32,178	+$5,600	$37,778

[a] Accumulated interest is now about $400.

[b] This fund is provided for emergency expenditures by the General Secretary when there is no time to secure prior approval by the Executive Committee.

[c] This fund must be held intact until all provisions of the will of Robert E. Horton are fulfilled.

[d] This fund, and anticipated future donations, will be held until the award is established.

Your Committee recommends that, when the new method of publishing the Transactions is well in effect, a study of the budget be made by the General and Executive Secretaries to make certain that costs are properly allocated between the two main items, Publication of Transactions, and General Office Expense. If possible, the results of this study should be available for use by the Budget Committee next year.

In the past when annual dues were $5, payment for a life membership was set at $100. The years of prepayment of annual dues by a lump sum may be computed by deducting one year of annual dues at the time of payment and yearly thereafter, and allowing 3 per cent interest on remaining balances. The results for various rates of dues are:

Initial Payment:	$100.	$100.	$100.	$150.
Annual Dues:	5.	7.	8.	8.
Prepaid Membership	29.6 yr	18.2 yr	15.3 yr	25.7 yr

It is recommended that the payment for life membership be raised to $150 beginning January 1, 1956.

A member may also obtain life membership when retiring from active professional service provided he has been a member for 15 years. It is recommended that the required length of membership be increased to 25 years for all members having less than 10 years of membership on January 1, 1956.

As the major part of income is received during the second half of a fiscal year, a rather large surplus ($4700) has been provided to meet the needs of the first half of fiscal year 1957.

APPENDIX 2--INTERIM REPORT OF SUBCOMMITTEE ON FORMAT

Walter B. Langbein, Chairman
Charles S. Gilman David G. Knapp

The Executive Committee has directed that beginning with the February, 1956, issue, our Transactions should be published by letterpress or something closely approaching it in appearance. Specifically, we are to avoid irregular margins and monotony of font.

The Subcommittee on Format accepts this instruction as its point of beginning. Although many members have no strong aversion to the present typography, the Subcommittee concurs that making the Transactions a more attractive and readable journal will add greatly to the prestige of the Union and make the Transactions a more dignified medium for publication of works of high scientific quality.

In view of our long and generally satisfactory experience with the offset method, your Subcommittee first looked into the possibilities of obtaining results specified by the Executive Committee. Justified margins can be obtained with present equipment by means of re-typing. Special composing machines are available for office use, such as Varityper, and the Coxhead machine that would not only provide justified margins but certain variety in use of type, as well. The Justo-writer offers a mechanical means for obtaining justified copy, with only single typing on tape, from which final copy is typed automatically.

The AGU was in a sense a pioneer in the use of photo-offset lithography in a standard journal. In fact it might be said that we owe the successful development of the Union to Dr. Fleming's expert use of this economical method. As matters stand, the Executive Secretary is exploiting fully all the possibilities of the offset method at the most economical level.

These methods would entail additional equipment and labor costs averaging about $4000 per year. Moreover, they would further engage the AGU staff in factory-like operations to the detriment of other equally necessary work of the Union. The Subcommittee felt rather strongly opposed to this extra load upon the AGU office, and in view of the extra cost, decided quite early not to consider these office typing methods further.

The Fotosetter is a professional composing machine, somewhat like the linotype in appearance and operation, which produces offset copy on film or paper. However, it would leave the AGU office with much of the work of final composition and making corrections in copy, and except for our sentimental attachment for offset reproduction it appeared to offer no marked advantage. The Fotosetter is used mostly for preparation of advertisements and text material. The AGU would have to bear the expense of preparing type matrices for a large array of mathematical symbols. A number of requests were made for quotation but the one we received for composition by the Fotosetter placed it out of competition. Obviously, the companies now engaged in Fotosetter composition are unfamiliar with composites of scientific literature.

Our considerations then led us to letterpress, and practical questions of page size, type face, and related matters of format. We studied and tabulated character density and legibility of many scientific journals. Our goals are economy and legibility. We cannot afford a luxury-type journal like Geographical Review, but want more prestige than we have now.

At present we obtain about 115 letters and numerals per square inch of printed page with a type face roughly equivalent to 9 on 9. Other journals range from 65 for Geographical Review to 98 for Bulletin of the Geological Society of America.

There are other considerations. Page size involves a choice between present or larger page. The present size (or nominal variations) has several advantages, among which perhaps continuity is most important. A material increase in size would inconvenience members and libraries in the way of shelf adjustments. (In some libraries octavo and quarto volumes are filed separately.) The present size is easily handled and carried for ready reference. Reprints are easily filed.

A larger size potentially offers advantages of greater economy. The relative space devoted to margins decreases as page size increases.

Two column format also offers economies. Side margins may be narrower, and blank space is less.

However, these potential savings must be considered in relation to the abilities and facilities of the printing houses. Two firms expressed keen desire to undertake the printing of the Transactions. The total cost of a 170-page edition of 6200 copies will be roughly $3400 including costs for reprints. This is about $900 per issue over our present costs.

We are now considering two alternatives on a 7 × 9 inch page (approximately 1/4 inch larger each way than present size).

(1) 9 on 11 type face, two-column format 33 × 52 pica printed area

(2) 10 on 12 type face, one-column format 33 × 52 pica printed page

For both alternates, references, bibliographic material, reviews, minutes, and similar material would be two-columns, 8 on 9 face. Article abstracts would be 8 on 10 face, 27 pica line.

The two-column format above is very close to that of the Bulletin of the Geological Society of America, except that page will be about 1/2 inch wider and columns each one pica wider.

We are also considering alternate page sizes and the propositions of two companies:

	Company 'A'	Company 'B'
Printed area	47.6 sq in	43.5 sq in
Page size	68.75 sq in	60 sq in
Ratio	69 pct	72.5 pct
Type	9 on 11 old style	9 on 10 new style
Character density	132	132

Note that character density is the same, because old style has higher density for equivalent point size.

We are also considering redesigning the cover. The cover is our trade mark, but it can be dressed up profitably without altering its general appearance. After major problems of page size are settled, mock-ups will be prepared for study by the Editorial and Publication Committee. The counsel of artists on the staffs of the printing house are also available. It was felt that none of the cover should be sold for advertising.

The Editorial and Publication Committee has yet considerable study before it can reach a final decision on format for next year's Transactions. Suggestions for its guidance are welcome.

REGIONAL MEETING HELD IN IOWA CITY, IOWA, JUNE 16-17, 1955

The North Central Region of AGU held its Second Conference in the Shambaugh Lecture Room of the Library of the University of Iowa, June 16-17, 1955. Forty-seven attended and participated in this Conference at which ten papers on climatology, meteorology, and the flow of water over and through the ground were presented. Tentative plans are being made to hold the next meeting in the St. Louis area.

M. C. Boyer, Chairman

SPECIAL ANNOUNCEMENTS

Display advertising accepted in the Transactions--In this issue of the *Transactions* you will note the first advertising that has ever appeared in the *Transactions*. It is now the policy, as noted previously, to open the pages of the *Transactions* to display advertising germane to geophysics. Persons who are interested in this matter should write to AGU's advertising representative, William A. James, 217 Canner Street, New Haven 11, Connecticut.

Back issues of the Transactions--Attention is called to the fact that back numbers of the *Transactions* for 1953 and earlier will possibly cease to be available through the office of AGU as we are tentatively planning to make arrangements with a reprinting firm for the reprinting of back numbers in order that full sets of the *Transactions* may be supplied by the reprinting firm at some advance in price. In Part 2 of the December, 1954, issue, pages 129-130, is a list showing which numbers are still available. Should you desire any of these, it is urged that you make arrangements to secure them at an early date directly from the office of AGU.

Election of officers of the Union and of the Sections in February, 1956--Attention is called to the fact that the terms of the incumbent elected officers of the Union and of the Sections expire June 30, 1956, and according to a schedule set up [see December, 1946, issue of *Transactions*, pp. 910-914], the Nominating Committees of the Union and of the Sections are now busily at work selecting the official nominees. If you have ideas with regard to these matters, get into touch with the appropriate Nominating Committee [see *Transactions*, December, 1954, pt. 2, pp. 125-128, and June, 1955, pp. 560-561, for names of those on Nominating Committees]. Communications addressed to the office of AGU will also be forwarded appropriately.

Mid-Pacific Regional Meeting to be held in Honolulu, Hawaii, November 15-18, 1955--Plans are progressing well for this first four-day meeting to be held under the auspices of the Geophysical Society of Hawaii, which is the regional group of the American Geophysical Union, and the local chapter of the American Meteorological Society. There will be sessions on various aspects of meteorology including weather forecasting, tropical meteorology, cloud physics, and agricultural meteorology, and sessions in Oceanography, Hydrology, Volcanology, and Seismology, as well as a field trip on November 18-19. The meeting will be held at the Reef Hotel on Waikiki Beach. For details, write to the Secretary of the Geophysical Society of Hawaii, Lawrence E. Eber (P. O. Box 3166, Honolulu, Hawaii).

Pacific Northwest Regional Meeting to be held in Portland, Oregon, November 18, 1955--Plans are progressing for a Regional Meeting to be held by the Pacific Northwest Regional Committee at Portland, Oregon, November 18, 1955. For further information or to send word concerning a paper that you would like to present, get into touch with the newly designated Chairman of the Committee, Milton S. Sachs, Bonneville Power Administration, P. O. Box 3537, Portland 8, Oregon.

Meeting of AGU in Atlanta, Georgia, December 27-29, 1955--The 122nd meeting of the American Association for the Advancement of Science will be held in Atlanta, Georgia, December 26-31, 1955. In connection with this, the AGU, which is now formally affiliated with the Association, will have its own program and be sponsor of other programs including an extensive symposium on the International Geophysical Year, 1957-58. It is planned that the symposium will be held on three successive mornings, December 27-29, and that the afternoons of those days will be devoted to a special AGU program, the details of which are being arranged by the *Ad Hoc* Southeastern Regional Committee under the chairmanship of Werner A. Baum. Interested persons should write to Dr. Baum at the Department of Meteorology, Florida State University, Tallahassee, Florida.

Pacific Southwest Regional Meeting to be held in California in late January or early February--Although details have not been received concerning the time or place of the meeting, plans are under way for the usual Regional Meeting to be held somewhere in California in late January or early February, 1956. Interested persons should write to Martin R. Huberty (Professor of Irrigation, University of California, 59 Physics-Biology Building, Los Angeles 24, California), Chairman of the Regional Committee, or to R. Corday Counts, Jr. (1472 Cortez Avenue, Burlingame, California), who is Secretary.

Thirty-Seventh Annual Meeting to be held in Washington, D. C., April 30-May 2, 1956--As announced in the June issue of the *Transactions* (p. 569), the Thirty-Seventh Annual Meeting will be held in Washington, D. C., April 30-May 2, 1956. This will serve as a first call to remind you to send in titles for papers for the program and for general suggestions in this regard. Watch SPECIAL ANNOUNCEMENTS for October and subsequently for further details.

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TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

Volume 36 October 1955 Number 5

NEGATIVE OXYGEN IONS IN THE UPPER ATMOSPHERE: THE AFFINITY AND RADIATIVE ATTACHMENT COEFFICIENT OF ATOMIC OXYGEN

L. M. Branscomb and S. J. Smith

Abstract--The influence of negative ions of atomic oxygen on the physics of the ionosphere and night airglow is re-examined in the light of new experimental determinations of the oxygen affinity (1.48 ± 0.10 ev) and photodetachment cross section. The radiative attachment coefficient is calculated from the photodetachment cross section. There is no evidence of a resonance at the threshold, where the attachment coefficient is approximately 1.2×10^{-15} cm^3/sec.

Introduction--The formation and destruction of negative ions have often been considered as possible contributory mechanisms in the formation of the several layers of the ionosphere, and in the excitation of the night airglow spectrum. Neither atomic nor molecular nitrogen has been shown by experiment to form a stable negative ion. Only the properties of the oxygen ions, O^- and O_2^-, need be considered. In this paper we confine our discussion to the properties of the atomic negative ion.

It has been known for many years that the effective recombination coefficient for the free electrons in the E and F layers is much larger than that expected for radiative recombination of free electrons and positive ions. The radiative attachment of free electrons to oxygen atoms, forming negative ions, was proposed by MARTYN and PULLEY [1936] and elaborated by MASSEY [1937] as the explanation for a large effective recombination coefficient.

Subsequent detailed analyses by BATES and MASSEY [1946, 1947], BATES [1950a,b], and MITRA and JONES [1954a] have shown that above the D layer the net daytime attachment rate is not important in comparison with the dissociative recombination of electrons and positive molecular ions produced by charge exchange. Photodetachment keeps the daytime concentration of negative ions very low, and a large dissociative recombination coefficient has been experimentally confirmed [GERJUOY and BIONDI, 1953].

At night the electronic and atomic densities in the F layer are too low for an appreciable buildup of the negative-ion concentration. In the E layer an efficient mechanism for negative-ion destruction must exist to account for the absence of an observable nocturnal buildup of negative-ion density [GERJUOY and BIONDI, 1953].

The exact rate of the radiative formation of O^- ions has not been known. The work of LOZIER [1934] and HAGSTRUM [1951] suggested the existence of excited states of O^- lying very near the continuum, which might give rise to resonant attachment of electrons with thermal energies, but their occurrence was judged to be unlikely on theoretical grounds by BATES and MASSEY [1943]. Such a resonance might make a difference by perhaps a factor of 30 in the attachment coefficient near the threshold, complicating the problem of explaining the lack of a buildup in negative-ion density in the E layer at night.

BATES and SEATON [1950] and BATES and MASSEY [1951] have also tentatively suggested that Lyman alpha radiation during solar flares may be responsible for apparent increases in ionospheric electron densities. MITRA and JONES [1954b] have suggested that this phenomenon must be explained by direct photoionization in the upper atmosphere. It has also been suggested that predawn increases in electron density are at least partly caused by visible radiation from the sun penetrating great distances at extremely oblique angles.

Negative ions, formed in the upper atmosphere by any means, may be influential in other ways, for example in the excitation of the spectra of the airglow and aurora [BATES and DALGARNO, 1953]. This excitation can come about through inelastic charge-transfer reactions between negative and positive ions. In such mutual-neutralization collisions the difference between the ionization potential and the electron affinity is available as excitation of the neutral products.

To evaluate these possibilities it is important to determine the electron affinity, photodetachment cross section and radiative attachment coefficient for 0^-. These quantities are required for the computation of the negative-ion concentration.

The affinity of 0^- has been determined by several methods, of which the most reliable is generally taken to be dissociative attachment by electron impact. The work of LOZIER [1934] and HAGSTRUM [1951] not only required the 2.2 ev dissociation energy but also the assumption that many 0^- ions are created in excited states lying near the continuum. It was this conclusion that lead to the investigation of the resonant attachment cross section by BATES and MASSEY [1943].

Results--We have measured the cross section for photodetachment of electrons from 0^- ions in a crossed beam experiment [BRANSCOMB and SMITH, 1955 a]. The details are described elsewhere [BRANSCOMB and SMITH, 1955 b] and [SMITH and BRANSCOMB, 1955]. Briefly, however, a beam of mass-separated, mono-energetic 0^- ions is illuminated in high vacuum with intense visible and near infrared radiation. The radiation is modulated, so that an alternating current of photodetached electrons is produced and distinguished from the d.-c. background of scattered ions and collisionally detached electrons. All of the modulated photodetached electrons are extracted from the beam with weak inhomogeneous electric and magnetic fields and the current is measured with a phase-sensitive detector.

By interposing glass absorption filters or interference reflection filters in the light beam, the spectral distribution of the radiation can be altered to permit a low-resolution study of the shape of the detachment cross section as a function of wavelength. It was immediately clear that a resonance in the detachment cross section of the sort described by BATES and MASSEY [1943] did not prevail, the cross section as a function of photon energy being more nearly parabolic in shape.

It has been shown by MASSEY [1950] that if the energy of the excited $2s^2\ 2p^4\ 3s$ configuration of 0^- lies well into the continuum, the resonance will not occur and the detachment and attachment cross sections near threshold will be dominated by the capture of electrons from s-continuum states. Electrons captured from initial d states will contribute to the radiative attachment cross section when the electron velocity is at least

$$v \approx 5^{0.5}\ h/2\pi ma \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where a is an interaction distance of the order of atomic dimensions. For the capture of s electrons, which have zero angular momentum with respect to the neutral atom, the attachment coefficient will be independent of velocity.

The cross sections for photodetachment and radiative attachment are related by the principle of detailed balancing

$$\sigma^r_{det} = (mvc/h\nu)^2\ (g_0/g_-)\ \sigma^r_{att} \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where v is the electron velocity, ν the photon frequency, and g_0 and g_- are the statistical weights of the neutral atom and negative ion respectively. The ground-state term is $^3P_{0,\,1,\,2}$ for the neutral atom and $^2P_{1/2,\ 3/2}$ for the negative ion. Therefore, the ratio of statistical weights is 9:6. Writing U for the photon energy $h\nu$, E for the electron kinetic energy, and E_0 for the affinity, all expressed in electron volts, (2) becomes

$$\sigma^r_{det} = [1.533 \times 10^6\ (U - E_0)/U^2]\ \sigma^r_{att} \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

The measured photodetachment cross section rises from a threshold at 8380A to a maximum of about 9×10^{-18} cm^2 at 5000 A.

Since the attachment coefficient α is equal to the product of the electron velocity and the radiative attachment cross section, we can express the attachment coefficient in terms of the observed photodetachment cross section as follows:

$$\alpha = 38.69\ (E + E_0)^2\ E^{-0.5}\ \sigma^r_{det} \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

We have used (4) to calculate α. The result is shown in Figure 1 as curve A. Curves B and C are taken from the calculations of BATES and MASSEY [1943], who used a 2.2 ev affinity for

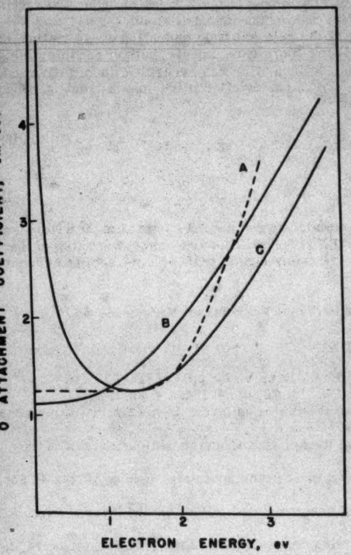

Fig. 1--Experimental and theoretical radiative attachment coefficients for atomic oxygen; the attachment coefficient is equal to the product of electron velocity and attachment cross section; Curve A is calculated from the experimental photodetachment cross section; Curves B and C are those calculated by BATES and MASSEY [1943], B assuming no excited state near the continuum and C assuming resonant capture of s electrons

oxygen. Curve B represents their best estimate of the attachment coefficient using the available estimates of the most probable polarizability of neutral oxygen. Curve C shows the resonance which is expected should the 3s orbital in O^- be slightly bound. Although the shape of the photodetachment cross section from which we calculated is not unambiguously determined [SMITH and BRANSCOMB,1955], it is clear from its general shape that there is no evidence of a resonance. Hence we find no evidence of the presence of excited states.

The wavelength of the threshold for photodetachment corresponds to the minimum energy for the removal of an electron from the negative ion to infinity with no excess kinetic energy. This energy is the electron affinity of the atomic oxygen. The detection of this threshold yields an affinity of 1.48 ± 0.10 ev, in contradiction with previous experiments, although in general accord with empirical extrapolations. This smaller affinity, used in (4), combined with a larger observed detachment cross section than that anticipated by Bates and Massey, result in a value of the radiative attachment coefficient at the threshold very close to that calculated by Bates and Massey. We find $\alpha_0 = 1.24 \times 10^{-15}$ cm^3/sec. This value must be considered rather tentative, for it is sensitive to the shape of the detachment cross section near the threshold, and it is precisely this region which is difficult to measure experimentally. It should be reliable within about 30 pct.

Discussion--The reduction of the atomic oxygen affinity from 2.2 ev to 1.48 ev has a number of minor consequences which may be enumerated:

(1) The lower affinity will result in a decrease in the estimated daytime O^- ion concentration because of the additional solar energy between the thresholds corresponding to the 2.2 and 1.48 ev affinities. About 28 pct of the energy from 6000 degree black body lies between 5640 and 8380 A.

(2) The 1.48 ev affinity makes deactivation of metastable oxygen atoms in the ^1D state energetically possible. This reaction

$$O^-\ (^2P) + O\ (^1D) \longrightarrow 2\,[O\ (^3P)] + e \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

has been considered by SEATON [1954], who investigated the possibility that the enhancement of the oxygen red lines in sunlit auroras might be caused by the destruction of the O^- ions. This mechanism is expected to be of importance only in very faint low-altitude auroras.

(3) Excitation of the oxygen red lines in the airglow by second-kind collisions with metastable negative oxygen ions is energetically impossible. Furthermore, there is no strong evidence that the metastable state exists.

(4) If the continuum from the radiative attachment of free electrons to oxygen atoms at high altitudes is detectable in the night airglow spectrum, this continuum will occur in the infrared from 7000 to 8000 A, rather than in the yellow-green, as formerly assumed.

(5) Because of the penetrability in the atmosphere of infrared radiation allowed by the decrease with wavelength of Rayleigh scattering, the lower affinity makes somewhat more plausible the suggestion that predawn ionization is produced by long-wavelength photodetachment.

Although attachment does not contribute appreciably to the determination of the daytime electron density above the D layer, attachment must be considered in the E layer at night. The radiative attachment cross section for 0^- and the dissociative recombination coefficients for 0_2^+ and N_2^+ have been experimentally determined. A number of the relevant photoionization cross sections have been measured. It is now of great importance that two more experiments, both of considerable difficulty, be performed. (1) Charge-exchange cross sections at thermal energies for negative and positive ions, atomic and molecular, are needed. (2) The rates of negative-ion destruction by exothermic associative detachment must be measured

$$0^- + 0 \rightarrow 0_2 + e \quad \ldots\ldots (6)$$

and

$$0^- + 0_2 \rightarrow 0_3 + e \quad \ldots\ldots (7)$$

Since we have shown that the rate of formation of atomic-oxygen negative ions at night will be very nearly equal to that estimated by BATES and MASSEY [1943] without resonance, the rates of the destructive processes, (6) and (7), need not be unreasonably large ($\sim 10^{-15}$ cm^3/sec) to keep the electron density from dropping in the E layer at night.

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LABORATORY STUDIES OF GRAVITY WAVES GENERATED BY THE MOVEMENT OF A SUBMERGED BODY

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Abstract--In order to gain some insight into the phenomenon of gravity waves generated by underwater seismic disturbances, the tsunami, a laboratory study was made of the waves resulting from an idealized two-dimensional model of the movement of a submerged body. Bodies of several shapes, sizes, and weights were allowed to drop vertically or to slide down inclines of several angles, in water of various depths, from several heights above the bottom, but always below the water surface. The surface time histories were recorded at a point close to the origin of the disturbance, and at a point or points some distance from the origin. In addition, motion pictures were taken of several of the tests. It was found that a crest always formed first, followed by a trough from one to three times the amplitude of the first crest (depending primarily upon the slope of the incline), followed by a crest with about the same amplitude as the trough. Because of the dispersive qualities of the waves, additional crests and troughs continued to form with increasing distance from the origin. The magnitude of the amplitudes depended primarily upon the submerged weight of the body, but also upon the depth of submergence, the water depth, and other characteristics of the generation. Within the limits of experimental conditions, it was found that the time intervals between the first and second crests remained constant regardless of the water depth, the distance of fall, the weight of the body or the time of the fall. It was, however, found to be related to the length of the body, with the period increasing with increasing length, and to the slope of the incline, with the smaller the incline the greater the period.

Introduction

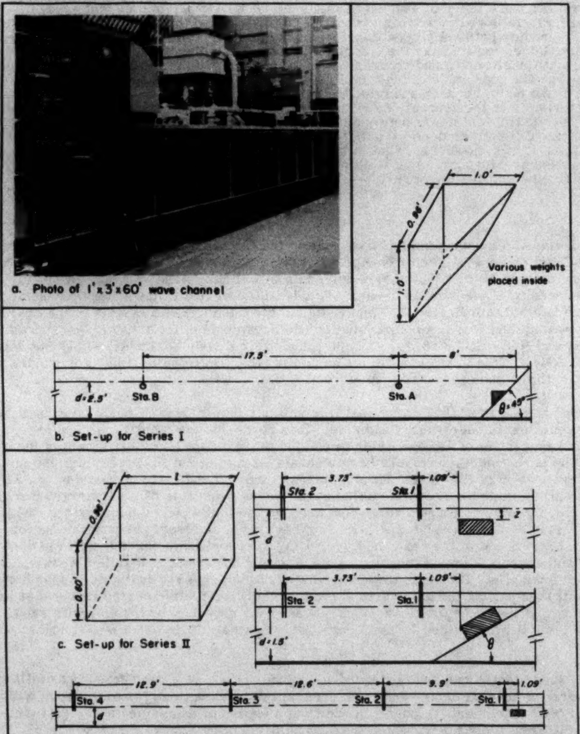
The tsunami which caused so much damage to the Hawaiian Islands and to many locations along the Pacific Coast of North America on April 1, 1946 was caused by a movement of the sea bottom on the northern slope of the Aleutian Trough, south of Unimak Island, Alaska [SHEPARD and Others, 1950]. The severity of the damage created considerable interest in the general phenomenon. A review of the literautre indicated that many studies had been made of certain of the characteristics of actual tsunamis, and that theoretical studies had been made of the Cauchy-Poisson wave phenomenon [UNOKI and NAKANO, 1953, for example], but that only one laboratory study had been made [TAKAHASI, 1934]. This study was for the case of waves generated by a plunger moving vertically in a well beneath the bed of a small channel.

SHEPARD and Others [1950] state that it is unlikely that a tsunami could be caused by dipolar disturbance, such as an underwater landslide. This reasoning apparently also applies to the case of the vertical movement of a block which is compensated for by a like movement in the opposite direction. The experiments described herein should be significant in determining the justification or lack of justification of this statement. A series of experiments was undertaken by SAUER and WIEGEL, [1946] to study the characteristics of the waves generated by a submerged body sliding down a 1/1 slope in a 60-ft channel three feet deep by one foot wide. Exploratory work, just prior to the first series of tests, consisted of piling coarse gravel as steeply as possible on top of a piece of sheet metal at one end of the channel, then pulling the sheet from under the pile to destroy its equilibrium and cause a slide. However, a true slide did not result, but rather a slump occurred in the center of the pile. The next attempt consisted of placing a vertical gate in the channel, piling sand behind it, then pulling the gate vertically out of the water; however, the removal of the gate generated waves of the same order of magnitude as those produced by the slumping sand. As a result of these tests it was decided to use a box sliding down an incline as a model underwater landslide.

Recently these tests have been extended to include a study of a submerged body falling vertically through water of several depths and from several initial elevations for each depth, with the effect of weight and body movement included. In addition, a series of experiments was performed to study the effect of different slopes down which the body slid.

Experimental procedure

Most of the experimental work was performed in a 60 ft glass-walled wave channel 3 ft deep by 1 ft wide in the Fluid Mechanics Laboratory of the University of California, Berkeley (Fig. 1a). The first set of experiments (Series I) consisted of generating waves by allowing a submerged wooden box to slide freely down an incline with a 1/1 slope (Fig. 1b). The box was triangular in cross section (12 × 12 in) and extended across the width of the channel. Six different weights at each of three initial elevations were investigated (Table I). Two Stevens Wave Recorders were used to record the waves. Previous tests with these recorders indicated that under laboratory conditions these recorders would determine wave height with a probable error of ± 12 pct [PUTNAM and ARTHUR, 1948]. One was located eight feet (Station A), and the second 25.5 ft (Station B) from the intersection of the water surface and the inclined board down which the box slid. The far end of the channel was equipped with an inclined beach to minimize reflection; even so, some reflection occurred and was apparent after the second wave crest. The water depth was maintained at 2.5 ft.


1.0'
0.96'
1.0'
Various weights placed inside
17.5'
8'
d=2.5'
Sta. B
Sta. A
θ=45°
l
0.96'
0.60'
3.75'
1.09'
Sta. 2
Sta. 1
z
d
3.75'
1.09'
Sta. 2
Sta. 1
d=1.5'
θ
12.9'
12.6'
9.9'
1.09'
Sta. 4
Sta. 3
Sta. 2
Sta. 1
d

a. Photo of 1'x3'x60' wave channel

b. Set-up for Series I

c. Set-up for Series II

Fig. 1--General laboratory set-up

Table 1--Body sliding down a slope of 1/1, Series I

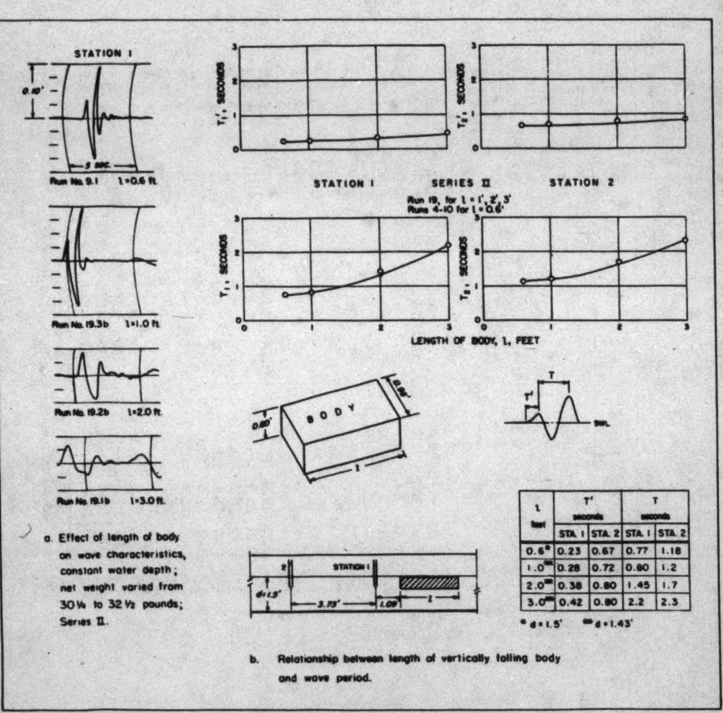
Run	d	z	W_{net}	PE_{net}	t	V	Station A					Station B				
							H'_A	H_A	H''_A	T'_A	T_A	H'_B	H_B	H''_B	T'_B	T_B
	ft	ft	lb	ft lb	sec	ft/sec	ft	ft	ft	sec	sec	ft	ft	ft	sec	sec
I-1A	2.5	0.00	2.3	3.5	7.5	0.20	0.001	0.0005	trace	1.1	1.3	0.001	trace	0.001[a]	1.2	1.8[a]
I-1B	2.5	0.00	2.3	3.5	7.7	0.20	0.002	0.0005	trace	0.8	1.3	0.001	trace	trace	. .	1.8[a]
I-2A	2.5	0.33	2.3	2.7	4.7	0.25	0.001	trace	0.0005[a]	1.0	2.0[a]	0.0005	trace	0.0005	1.0	1.5[a]
I-2B	2.5	0.33	2.3	2.7	4.9	0.24	0.001	trace	0.0005[a]	1.2	1.7[a]	0.0005	trace	0.0005[a]	1.0	1.6[a]
I-3A	2.5	0.83	2.3	1.5	3.1	0.22	0.0005	trace	trace	0.9	0.9[a]	0.0005	trace	0.010[a]	0.8	1.1[a]
I-3B	2.5	0.83	2.3	1.5	3.3	0.20	0.0005	trace	trace	1.0[a]	1.7[a]	0.0005	trace	trace	1.2	1.8[a]
I-4A	2.5	0.00	8.1	12.1	4.1	0.37	0.007	0.009	0.011	1.1	1.5	0.003	0.003	0.003	1.2	2.0
I-4B	2.5	0.00	8.1	12.1	4.1	0.37	0.006	0.005	0.007	1.0	1.6	0.003	0.002	0.002	1.1	1.9
I-5A	2.5	0.33	8.1	9.5	3.1	0.38	0.004	0.010[a]	0.005[a]	1.2	2.1[a]	0.002	0.005[a]	0.003[a]	1.2	3.1[a]
I-5B	2.5	0.33	8.1	9.5	2.9	0.40	0.004	0.010[a]	0.004[a]	1.2	2.1[a]	0.002	0.004[a]	0.002[a]	1.2	3.1[a]
I-6A	2.5	0.83	8.1	5.4	2.1	0.32	0.003	0.007	0.004[a]	1.0	2.3[a]	0.002	0.003	0.001[a]	1.2	2.6[a]
I-6B	2.5	0.83	8.1	5.4	2.1	0.32	0.003	0.007	0.004[a]	1.2	2.0[a]	0.002	0.003	0.001[a]	1.1	3.8[a]
I-7A	2.5	0.00	20.0	30.0	2.1	0.72	0.023	0.029[a]	0.013[a]	1.0	2.8[a]	0.013	0.019[a]	0.011[a]	1.2	3.5[a]
I-7B	2.5	0.33	20.0	30.0	2.3	0.65	0.024	0.038[a]	0.017[a]	1.1	2.8[a]	0.009	0.020[a]	0.010[a]	1.4	3.5[a]
I-8A	2.5	0.33	20.0	23.1	1.5	0.78	0.022	0.026	0.015	1.1	2.1	0.011	0.025	0.015	1.2	2.5
I-8B	2.5	0.33	20.0	23.1	1.5	0.78	0.022	0.036	0.026	1.0	2.1	0.012	0.026	0.012	1.2	2.3
I-9A	2.5	0.83	20.0	13.4	1.1	0.61	0.016	0.027	0.020	1.0	1.8	0.007	0.013	0.017	1.2	2.1
I-9B	2.5	0.85	20.0	13.4	1.1	0.61	0.015	0.026	0.022	1.0	1.9	0.005	0.013	0.016	1.2	2.2[a]
I-10A	2.5	0.00	23.9	35.8	1.9	0.79	0.030	0.028	0.032[a]	1.2	2.6[a]	0.018	0.029[a]	0.012[a]	1.2	2.7[a]
I-10B	2.5	0.00	23.9	35.8	2.1	0.72	0.028	0.046	0.018[a]	1.0	2.3[a]	0.018	0.024[a]	0.013[a]	1.2	2.8[a]
I-11A	2.5	0.33	23.9	28.0	1.5	0.78	0.030	0.052	0.031	1.0	1.9	0.014	0.033	0.031	1.2	2.4
I-11B	2.5	0.35	23.9	28.0	1.5	0.78	0.029	0.053	0.033	0.9	1.9	0.015	0.033	0.046	1.2	2.3
I-12A	2.5	0.83	23.9	16.0	1.1	0.61	0.018	0.036	0.021	0.8	1.8	0.007	0.016	0.019	1.2	2.2
I-12B	2.5	0.83	23.9	16.0	0.9	0.75	0.018	0.036	0.024	0.8	1.8	0.007	0.012	0.020	1.1	1.9
I-13	2.5	0.00	35.3	53.2	1.8	0.84	0.038	0.047	0.028	1.1	1.7					
I-14	2.5	0.33	35.3	41.2	1.2	0.97	0.037	0.068	0.044	1.1	1.6					
I-15	2.5	0.83	35.3	23.8	0.8	0.84	0.022	0.037	0.027	1.0	1.7					
I-16	2.5	0.00	56.6	85.0	1.2	1.25	0.075	0.094	0.083	1.1	1.8					
I-17	2.5	0.33	56.6	66.2	0.8	1.47	0.050	0.093	0.062	1.1	1.7					
I-18	2.5	0.83	56.6	38.0	0.6	1.12	0.026	0.049	0.036	1.0	1.5					

[a] Uncertain due to reflection from far end of channel.

A second set of experiments (Series II) consisted of four parts:

(1) A submerged rectangular box 0.6 ft deep by 0.6 ft long, extending the width of the channel, was allowed to fall freely in a vertical direction in water of several depths (1.50, 1.92, and 2.66 ft) and from two or more submergences for each water depth. Seven different box weights (from 1-3/8 to 26 lb, net, submerged) at each depth and submergence were used. Two parallel-wire resistance elements were used to measure the waves. The first (Station 1) was located at a distance of 1.09 ft and the second (Station 2), 4.82 ft from the leading edge of the submerged body. A sloping beach was located at one end of the channel to absorb the waves, but the waves were reflected from the opposite end. However, the reflected waves arrived after the initial disturbance had completely passed the recording elements, and thus were of no consequence. The conditions are shown in Figure 1c and are presented in Table 2.

(2) A series of submerged rectangular boxes 0.6 ft deep by 1.0, 2.0, and 3.0 ft in length, extending the width of the channel, was allowed to fall freely in a vertical direction in water about 1.5 ft deep [Fig. 2]. The initial position of the box in all cases was such that the top was barely under the water surface, that is, at zero submergence. The net weight of the submerged box varied from 30.2 lb for the three-foot box to 32.2 lb for the one-foot box. Two parallel-wire resistance elements were used, and located as in (1), above.



l feet	T' seconds		T seconds	
	STA. I	STA. 2	STA. I	STA. 2
0.6*	0.23	0.67	0.77	1.18
1.0**	0.28	0.72	0.80	1.2
2.0**	0.38	0.80	1.45	1.7
3.0**	0.42	0.80	2.2	2.3

* d = 1.5' ** d = 1.43'

a. Effect of length of body on wave characteristics, constant water depth; net weight varied from 30¼ to 32½ pounds; Series II.

b. Relationship between length of vertically falling body and wave period.

Fig. 2--Effect of body length

Table 2--Box falling vertically, Series II

Run	d	z	W_{net}	PE_{net}	Station 1					Station 2				
					H_1'	H_1	H_1''	T_1'	T_1	H_2'	H_2	H_2''	T_2'	T_2
	ft	ft	lb	ft lb	ft	ft	ft	sec	sec	ft	ft	ft	sec	sec
II-4.1	1.92	0.0	26.	34.3	0.027	0.090	0.083	0.2	0.75	0.013	0.038	0.064	0.6	1.15
II-4.2	1.92	0.0	20.5	27.0	0.026	0.078	0.075	0.25	0.7	0.012	0.035	0.054	0.6	1.20
II-4.3	1.92	0.0	16.6	22.0	0.024	0.076	0.071	0.2	0.75	0.012	0.034	0.054	0.65	1.15
II-4.4	1.92	0.0	12.8	16.8	0.018	0.052	0.060	0.35	0.75	0.012	0.029	0.041	0.65	1.2
II-4.5	1.92	0.0	8.8	11.5	0.014	0.041	0.012	0.3	0.8	0.009	0.027	0.032	0.7	1.2
II-4.6	1.92	0.0	5.1	6.8	0.011	0.028	0.009	0.3	0.9	0.007	0.019	0.017	0.7	1.2
II-4.7	1.92	0.0	1.4	1.8	0.0005	0.004	trace	0.3	0.45	0.003	0.002	0.010	0.4	1.2
II-5.1	1.92	0.5	1.4	1.1	trace	0.002	0.0005	. .	0.7	0.0005	0.0005	trace	0.7	1.15
II-5.2	1.92	0.5	5.1	4.2	0.0005	0.011	0.004	0.25	1.0	0.003	0.009	0.010	0.6	1.2
II-5.3	1.92	0.5	8.8	7.2	0.001	0.021	0.018	0.3	0.75	0.004	0.013	0.019	0.7	1.15
II-5.4	1.92	0.5	12.8	10.4	0.002	0.027	0.026	0.2	0.7	0.005	0.015	0.021	0.6	1.15
II-5.5	1.92	0.5	16.6	13.6	0.002	0.032	0.031	0.3	0.7	0.006	0.015	0.024	0.7	1.15
II-5.6	1.92	0.5	20.5	16.8	0.002	0.033	0.037	0.25	0.75	0.006	0.016	0.026	0.6	1.2
II-5.7	1.92	0.5	26.	21.3	0.002	0.034	0.038	0.2	0.65	0.006	0.017	0.027	0.6	1.1
II-6.1	1.92	0.25	26.	27.8	0.014	0.062	0.071	0.2	0.65	0.010	0.030	0.041	0.7	1.2
II-6.2	1.92	0.25	20.5	22.0	0.012	0.055	0.073	0.2	0.7	0.010	0.025	0.042	0.65	1.2
II-6.3	1.92	0.25	16.6	17.8	0.004	0.044	0.054	0.3	0.8	0.008	0.023	0.035	0.7	1.2
II-6.4	1.92	0.25	12.8	13.6	0.008	0.045	0.061	0.2	0.8	0.005	0.023	0.038	0.6	1.2
II-6.5	1.92	0.25	8.8	9.4	0.006	0.036	0.035	0.2	0.7	0.008	0.018	0.028	0.7	1.2
II-6.6	1.92	0.25	5.1	5.5	0.004	0.022	0.014	0.2	0.95	0.006	0.014	0.018	0.7	1.2
II-6.7	1.92	0.25	1.4	1.5	0.0005	0.004	trace	0.2	0.9	0.001	0.0005	0.002	0.7	1.2
II-7.1	2.66	0.0	26.	53.6	0.026	0.098	0.080	0.2	0.65	0.018	0.044	0.070	0.6	1.25
II-7.2	2.66	0.0	20.5	42.3	0.026	0.098	0.070	0.25	0.7	0.019	0.044	0.070	0.7	1.25
II-7.3	2.66	0.0	16.6	34.2	0.024	0.078	0.072	0.25	0.7	0.017	0.041	0.061	0.65	1.25
II-7.4	2.66	0.0	12.8	26.3	0.022	0.071	0.061	0.25	0.7	0.013	0.037	0.048	0.7	1.25
II-7.5	2.66	0.0	8.8	18.0	0.016	0.042	0.039	0.25	0.7	0.009	0.029	0.027	0.7	1.25
II-7.6	2.66	0.0	5.1	10.8	0.009	0.024	0.006	0.25	0.9	0.005	0.015	0.006	0.7	1.25
II-7.7	2.66	0.0	1.4	2.8	0.009	0.012	0.002	0.25	0.8	0.003	0.010	0.008	0.7	1.15
II-8.1	2.66	0.5	1.4	2.1	trace	0.004	trace	. .	0.85	0.0005	0.002	trace	0.7	1.15
II-8.2	2.66	0.5	5.1	8.0	0.0005	0.018	0.004	0.2	0.8	0.004	0.013	0.008	0.7	1.2
II-8.3	2.66	0.5	8.8	13.6	0.0005	0.032	0.020	0.2	0.8	0.003	0.021	0.019	0.7	1.25
II-8.4	2.66	0.5	12.8	19.9	0.002	0.036	0.031	0.2	0.8	0.006	0.023	0.028	0.7	1.25
II-8.5	2.66	0.5	16.6	25.9	0.002	0.044	0.040	0.2	0.8	0.006	0.026	0.030	0.7	1.25
II-8.6	2.66	0.5	20.5	32.0	0.003	0.042	0.040	0.2	0.8	0.008	0.028	0.041	0.7	1.25
II-8.7	2.66	0.5	26.	40.5	0.004	0.050	0.052	0.2	0.75	0.008	0.030	0.037	0.6	1.25
II-9.1	1.50	0.0	26.	23.4	0.035	0.086	0.095	0.2	0.7	0.015	0.035	0.052	0.7	1.2
II-9.2	1.50	0.0	20.5	18.5	0.029	0.072	0.073	0.2	0.7	0.015	0.033	0.048	0.7	1.1
II-9.3	1.50	0.0	16.6	15.0	0.029	0.072	0.073	0.2	0.7	0.015	0.033	0.048	0.7	1.15
II-9.4	1.50	0.0	12.8	11.5	0.020	0.054	0.070	0.25	0.75	0.013	0.030	0.041	0.7	1.15
II-9.5	1.50	0.0	8.8	7.9	0.019	0.036	0.045	0.2	0.75	0.012	0.027	0.036	0.7	1.2
II-9.6	1.50	0.0	5.1	4.6	0.011	0.027	0.020	0.25	0.8	0.010	0.020	0.023	0.75	1.15
II-9.7	1.50	0.0	1.4	1.2	0.004	0.006	0.002	0.25	0.8	0.003	0.003	0.002	0.7	1.2
II-10.1	1.50	0.5	1.4	0.6	trace	0.0005	0.002	0.2	0.8	trace	0.0005	0.003	0.7	1.2
II-10.2	1.50	0.5	5.1	2.0	0.001	0.005	0.008	0.2	0.8	0.0005	0.004	0.008	0.7	1.1
II-10.3	1.50	0.5	8.8	3.5	0.002	0.010	0.010	0.2	0.7	0.002	0.007	0.011	0.7	1.2
II-10.4	1.50	0.5	12.8	5.1	0.003	0.013	0.016	0.2	0.7	0.002	0.003	0.011	0.7	1.2
II-10.5	1.50	0.5	16.6	6.7	0.004	0.017	0.018	0.2	0.7	0.003	0.008	0.013	0.6	1.2
II-10.6	1.50	0.5	20.5	8.2	0.005	0.019	0.020	0.2	0.6	0.004	0.007	0.015	0.7	1.1
II-10.7	1.50	0.5	26.	10.3	0.005	0.020	0.022	0.2	0.65	0.009	0.009	0.017	0.7	1.15

Table 3--Body sliding down slopes of various angles, Series II

Run	Grade	Angle	T_1'	T_2'	T_1	T_2	H_1'	H_2'	H_1	H_2	H_1/H_1'	H_2/H_2'
		°	sec	sec	sec	sec	ft	ft	ft	ft		
14.1[a]	1:1.59	32.1	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .
14.2a	1:1.00	42.1	0 4	0.75	1.4	1.55	0.033	0.032	0.051	0.038	1.54	1.19
14.2b	1:1.00	42.1	0 5	0.7	1.4	1.55	0.032	0.035	0.053	0.035	1.65	1.00
14.2c[a]	1:1.00	42.1	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .
14.2d	1:1.00	42.1	0.5	0.6	1.5	1.65	0.030	0.026	0.042	0.031	1.40	1.19
14.2e	1:1.00	42.1	0.5	0.7	1.75	1.95	0.032	0.026	0.032	0.026	1.00	1.00
14.3a	1:0.75	53.1	0.45	0.8	1.1	1.35	0.046	0.042	0.080	0.070	1.74	1.67
14.3b	1:0.75	53.1	0.45	0.7	1.25	1.4	0.039	0.036	0.073	0.061	1.87	1.70
14.3c	1:0.75	53.1	0.45	0.7	1.2	1.4	0.044	0.040	0.072	0.060	1.63	1.50
18.1[a]	1:2.08	25.7	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .
18.2a	1:1.60	32.0	0.6	0.9	2.65	2.7	0.027	0.030	0.044	0.037	1.63	1.23
18.2b	1:1.60	32.0	0.6	0.9	2.3	2.6	0.031	0.031	0.043	0.037	1.39	1.20
18.2c	1:1.60	32.0	0.55	1.0	2.5	2.9	0.027	0.027	0.044	0.037	1.63	1.37
18.3a	1:1.08	42.8	0.55	0.9	1.35	1.6	0.041	0.035	0.064	0.060	1.56	1.71
18.3b	1:1.08	42.8	0.5	0.9	1.35	1.55	0.047	0.040	0.070	0.062	1.49	1.55
18.3c	1:1.08	42.8	0.4	0.9	1.35	1.5	0.047	0.040	0.072	0.064	1.54	1.60
18.4a	1:0.74	53.5	0.5	0.9	1.25	1.3	0.055	0.040	0.082	0.070	1.49	1.75
18.4b	1:0.74	53.5	0.45	0.85	1.2	1.4	0.055	0.039	0.087	0.075	1.58	1.92
18.4c	1:0.74	53.5	0.55	1.0	1.1	1.3	0.052	0.040	0.086	0.072	1.65	1.80
18.4d	1:0.74	53.5	0.55	0.9	1.2	1.25	0.059	0.041	0.084	0.070	1.43	1.71
20.1[a]	1:2.40	22.7	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .
20.2a	1:1.83	28.7	0.6	1.0	2.7	2.9	0.022	0.028	0.024	0.025	1.08	0.89
20.2b	1:1.83	28.7	0.7	1.0	2.8	2.9	0.024	0.026	0.029	0.023	1.21	0.88
20.2c	1:1.83	28.7	0.6	1.0	2.5	2.7	0.020	0.026	0.039	0.033	1.95	1.27
20.3	1:1.83	28.7	0.5	0.9	2.3	2.2	0.019	0.024	0.034	0.035	1.79	1.45
20.4a	1:1.37	36.3	0.5	0.9	1.6	1.7	0.040	0.040	0.066	0.050	1.65	1.25
20.4b	1:1.37	36.3	0.5	0.9	1.5	1.7	0.038	0.038	0.060	0.046	1.58	1.21
20.4c	1:1.37	36.3	0.5	0.9	1.5	1.7	0.039	0.040	0.062	0.046	1.59	1.15
20.5a	1:1.64	31.5	0.5	0.8	2.1	2.1	0.035	0.033	0.049	0.040	1.40	1.21
20.5b	1:1.64	31.5	0.5	0.9	2.1	2.2	0.033	0.034	0.048	0.034	1.45	1.00
20.5c	1:1.64	31.5	. .	. .	2.0	2.1	0.032	0.032	0.048	0.033	1.50	1.03
20.6a	1:2.06	26.3	0.6	1.0	2.3	3.3	0.018	0.020	0.021	0.020	1.17	1.00
20.6b	1:2.06	26.3	0.6	1.0	3.4	3.5	0.020	0.020	0.021	0.021	1.05	1.05
20.6c	1:2.06	26.3	. .	1.0	. .	3.2	. .	0.020	. .	0.020	. .	1.00
20.7[a]	1:2.44	22.3	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .
20.8a	1:2.24	24.2	0.5	0.9	4.0	4.4	0.010	0.012	0.021	0.016	2.10	1.33
20.8b[a]	1:2.24	24.2	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .
20.8c	1:2.24	24.2	0.5	0.9	3.6	4.0	0.014	0.016	0.020	0.015	1.43	0.94
20.8d	1:2.24	24.2	0.5	. .	4.0	4.2	0.014	0.016	0.017	0.012	1.22	0.75
20.9a	1:0	90.0	0.3	0.7	0.9	1.15	0.044	0.022	0.085	0.061	1.93	2.78
20.9b[a]	1:0	90.0	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .
20.9c	1:0	90.0	. .	0.7	. .	1.15	. .	0.025	. .	0.060	. .	2.40
20.9d	1:0	90.0	0.25	0.7	0.85	1.2	0.048	0.026	0.093	0.062	1.94	2.39

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[a] Run was no good as the body stuck for a short time during slide.

Note: Water depth varied from 1.43 feet to 1.50 feet.

(3) The box used in (1), above, fitted with two small, lightweight, metal runners on the bottom, was allowed to slide down an inclined metal plate with slopes ranging from vertical to 1/2.4 (22.7°) (Table 3). It was found that a slope of 24.2° was the flattest that the box would slide down in a uniform manner. The net submerged weight of the box was 20.5 lb and the water depth was between 1.43 and 1.48 ft. The highest point of the box at its initial position was at zero submergence. Two parallel-wire resistance elements were used, and located as in (1) and (2), above (Fig. 1c).

(4) A lead plate 3/16 by 6 inches, extending to the width of the channel, was allowed to drop in water 0.14, 0.24 and 0.36 ft deep and from two or more depths of submergence for each condition. The net submerged weight of the lead plate was 3.5 lb. Wave measurements were made by a series of four parallel-wire resistance elements located at 1.09 ft (Station 1), 10.96 ft (Station 2), 23.62 ft (Station 3), and 36.49 ft (Station 4) from the center of the submerged body (Fig. 1c). These tests were performed in a wave channel similar to the one used in the other tests.

Previous tests with the parallel wire resistance elements indicated that under laboratory conditions these recorders could determine wave height with a probable error of ±5 pct [MORISON, 1949].

In all cases the box was held in place by a cord, and after the surface of the water had quieted the cord was cut, allowing the body to fall or slide freely. A sloping beach located at one end of the channel effectively absorbed the waves. However, waves were reflected from the opposite end of the channel in the tests involving the vertically falling body. The reflected waves arrived after the initial disturbance had completely passed the recording elements and so presented no problem; in fact, an opportunity was given to illustrate the dispersive qualities of the phenomenon.

Results and discussion

Vertically falling body of constant size--The simplest case studied was that of a box falling freely in a vertical direction. The variables were water depth, initial depth of submergence, and the weight, in water, of the box. The results are presented in Table 2.

In Figure 3 are shown examples of the surface-time histories of the waves generated under conditions of constant water depth (1.50 ft and zero submergence, the top of the box barely under the water surface), but with varying weights of boxes. It can be seen that the initial disturbance was a crest, followed by a trough and then another crest. This was also true for all the experiments which were conducted. By the time the disturbance reached Station 2 (4.82 ft from the leading edge of the body) several waves had formed because of dispersion. In Figure 4 are shown examples of the surface-time histories of the waves generated: (1) in water of constant depth, but with the initial submergence depth of the body varying, and (2) with zero initial submergence, but with varying water depths.

The most interesting characteristic of the waves is their consistent 'period' (see Table 2). At Station 1 the time interval between no disturbance and the first crest varied between 0.2 and 0.35 sec, average 0.23 sec. The time interval between the first and second crest varied between 0.45 and 1.0 sec, average 0.77 sec. At Station 2 the time interval between no disturbance and the first crest varied between 0.4 and 0.75 with the average 0.67 sec, and the time interval between the first and second crests varied between 1.1 and 1.25 sec, average 1.18 sec. Within the limits of accuracy of the measurements and within the range of experimental conditions, it appears that the period of the waves is independent of the water depth, the initial depth of submergence of the body, and the weight of the body.

In Figure 5 are presented the relationships among body weight, water depth, submergence, and wave amplitude. It can be seen that the greater the body weight, the greater the wave amplitude for the same values of depth and of submergence. The effect of depth of submergence is just as apparent, with the greater the submergence the lower the wave amplitude, for the same values of body weight and water depth. However the relationship between water depth and wave amplitude is not entirely consistent. Within the range of experimental conditions, the effects of varying body weights and varying depths of submergence were large, whereas the effect of water depth was relatively small. In addition, the surface of the water usually broke above the body as it started to fall from its position of initial zero submergence, whereas the water surface did not break for the 0.50-ft submergence. The amplitudes of the waves which reformed thus were dependent upon the amount of energy lost in breaking as well as upon the other consitions. By the time the waves had reached Station 2 the effect of breaking had nearly disappeared. It can be seen that the amplitude of the waves decreased with decreasing water depth for given values of initial submergence and body weight.

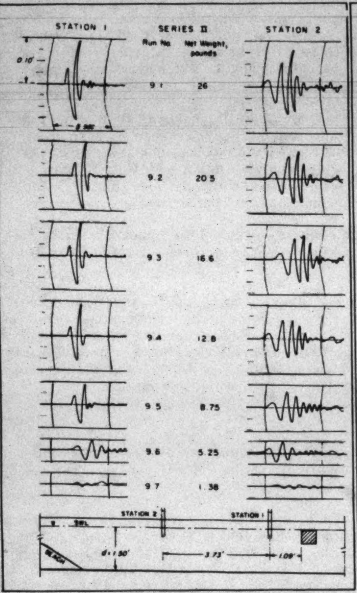
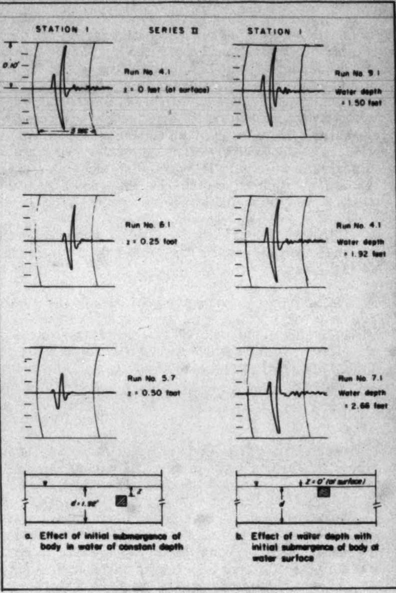


Fig. 3--Surface time histories for seven different weights for constant water depth and constant initial submergence of body



a. Effect of initial submergence of body in water of constant depth

b. Effect of water depth with initial submergence of body at water surface

Fig. 4--Effect of initial submergence and water depth

In Figure 6 are presented the relationships between amplitudes of the first crests and troughs and the second crests, at Stations 1 and 2. In addition, the correlation of the amplitude of the first trough at Station 1 with the amplitude of the first trough at Station 2 is shown. With the exception of the relationship between the amplitude of the first crest and the first trough at Station 1, there was apparently no effect of initial depth of submergence, and in no case was there an apparent effect of water depth or body weight.

In addition to the main body of tests, two additional runs were made. One was to determine the surface-time history over the center of the falling body. It was found that at this point a trough occurred first, followed by a crest of approximately the same amplitude. Following the crest, the surface rapidly resumed its still-water position. This tended to confirm the expectations that the disturbance, as measured a short distance from the source, was caused by the bottom of the body pushing water out, and the water having to move in over the box as it falls. The second test was made with ends mounted on the body so that when the body rested on the bottom the ends extended up through the water surface. In this case an entirely different type of wave was generated, which consisted of a single crest followed by a single trough. This wave traveled as an entity down the channel and did not disperse into several waves as was the case of the main body of tests.

Vertically falling bodies of different lengths--In Figure 2a are shown the surface time histories of the waves passing Station 1 for body lengths of 0.6, 1.0, 2.0 and 3.0 ft. The net submerged body weight, the water depth, and the initial depth of submergence were approximately the same for all lengths. In Figure 2b are shown the relationships between body length and 'period' between no disturbance and the first crest, and between the first and second crests, for Stations 1 and 2. Within

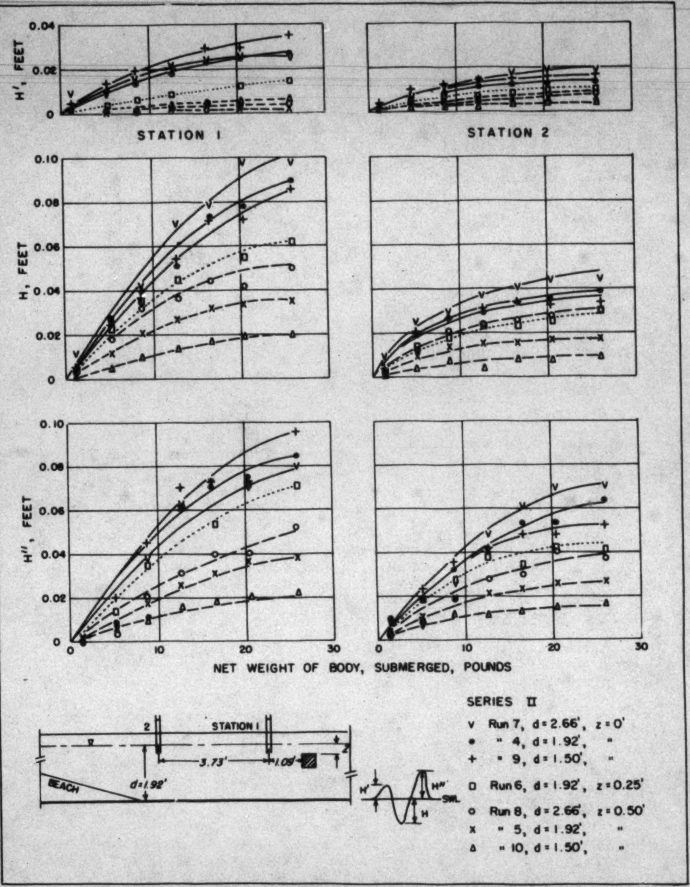


Fig. 5--Relationships among water depth, submergence, and amplitude of initial crest and trough and second crest, for vertically falling body

the range of experimental conditions, the initial period changed but slightly with increasing body length, while the period measured between the first two crests increased considerably with increasing body length.

Note that if the curve for T_1 in Figure 2 is extrapolated to a far greater degree than is prudent, one sees that a disturbance a few thousand feet in length would produce waves with an initial period of the order of from ten to fifteen minutes.

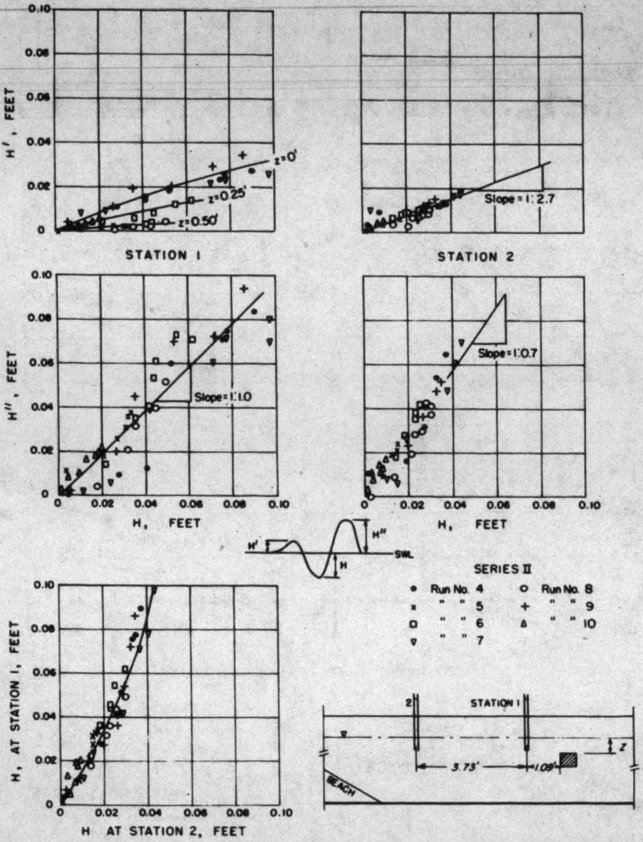
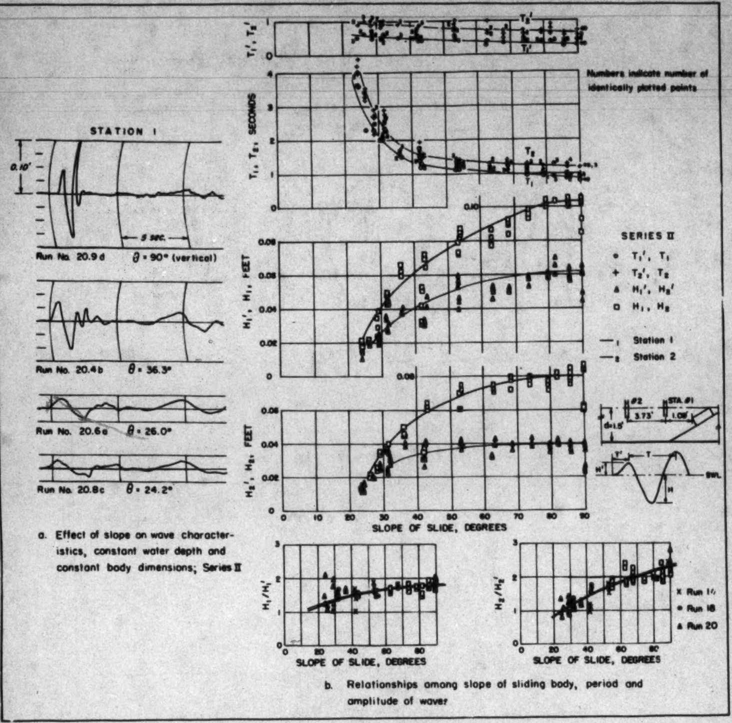


Fig. 6--Relationship among the amplitudes of the initial crest, trough and second crest for a vertically falling body

Body sliding down inclines--In Figure 7a are shown examples of the surface time histories of the waves passing Station 1 which were generated by a body sliding down inclines with slopes from 24.2 to 90°. In all cases the body size and weight, the water depth, and the initial depth of submergence were kept constant. The data on amplitude and period are shown in Figure 7b (see also Table 3). It can be seen that the period is related to incline slope, with the smaller the slope



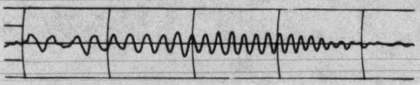
a. Effect of slope on wave characteristics, constant water depth and constant body dimensions; Series II

b. Relationships among slope of sliding body, period and amplitude of waves

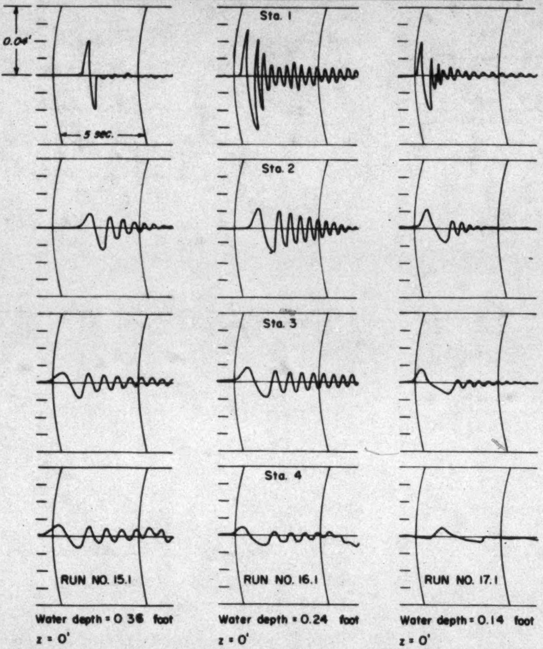
Fig. 7--Effect of incline angle

the greater the period. The period between no disturbance and the first crest is not nearly as sensitive to slope as the period between the first two crests. The amplitudes of the initial crests and troughs are smallest for the flattest slopes, increasing rapidly with increasing slope for the flatter slopes and becoming asymptotic to some maximum value as the slope approaches the vertical. Also shown are the relationships between the ratio of the amplitude of the initial trough to the initial crest and the incline slope for Stations 1 and 2. Although there is considerable scatter, it is evident that the ratio of the amplitudes of the initial troughs to the initial crests increases with increasing steepness of the incline.

In Table 1 are presented some data from Series I, on the effect of initial depth of submergence and net body weight on waves generated by the body sliding down an incline of 45° in water 2.5 ft deep. The relationships between amplitudes of initial troughs, crests, and second crests are more complex than was the case for the vertically falling body. This is understandable, considering the relationship between amplitudes at Station 1 and 2 for the vertically falling bodies, that is, the effect, due to dispersion, of travel distance. In these earlier tests, the wave recorders were mounted at fixed distances from the intersection of the still-water line and the incline. Hence, for the different initial depths of submergence, the distances changed (as measured from the edge of the body at the start of the slide to the wave recorders at Stations A and B).



a. Series II, Run 9.1; train of waves reflected from far end of channel



b. Series II; waves in water of various depths

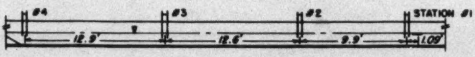


Fig. 8--Wave dispersion

The periods were not as consistent as those of the vertically falling body; however, a plot on statistical paper showed the scatter about the mean values to be due to normal error.

The limiting case of a body sliding down an incline might be that of a hydrofoil moving with constant velocity. Studies of this problem by LAITONE [1954] have shown that a single wave is formed which remains above the hydrofoil.

Table 4--Effect of dispersion

Series II, Run 9.1, period of train of waves

Between crests	Period T
	sec
1-2	1.3
2-3	1.35
3-4	1.0
4-5	1.1
5-6	0.95
6-7	0.95
7-8	0.95
8-9	0.75
9-10	0.80
10-11	0.75
11-12	0.70
12-13	0.70
13-14	0.75
14-15	0.70
15-16	0.65
16-17	0.65
17-18	0.60
18-19	0.60
19-20	0.60
20-21	0.55
21-22	0.55
22-23	0.55
23-24	0.55

Dispersion--The waves formed by the vertically falling and by the sliding bodies were not 'long waves'; that is, their velocities were dependent upon wave length as well as upon water depth. These waves, once they had traveled a short distance from the origin of the disturbance, exhibited characteristics of the Cauchy-Poisson waves, [UNOKI, and NAKANO, 1953]. In order to show the effect of travel distance, the disturbance was allowed to travel the length of the wave channel, reflect, and travel back again. As can be seen in Figure 8a and Table 4, the initial disturbance dispersed into at least 24 recognizable waves, the periods of which progressively shortened from a maximum for the first wave to a minimum for the last wave.

The height of the body used in the deeper water precluded its use in shallower water. In order to study the phenomena in shallow water, a lead plate of nearly the same plan dimensions as the body used in Runs 4-10 (Series II), but only 3/16 inch thick was dropped vertically in water 0.36, 0.24 and 0.14 ft deep. In Figure 8b are shown the experimental set-up and the surface time histories at four stations for an initial zero submergence in the three depths of water. The data from the tests are presented in Tables 5-7. It can be seen that the periods of waves remained constant for the three water depths at each station, but that they increased with increasing distance from the origin; hence, apparently dispersion was still present to some extent. However, the velocity of wave crest propagation compared very well with the theoretical velocity as given by the equation for 'long waves' ($\sqrt{gd}$, where g is the value of gravity and d is the water depth).

Table 5--Effect of dispersion

Series II

Series and run	d	z	W_{net}	PE_{net}	Between stations	Velocity of disturbance			
						Δx	Δt	C_m	C_t
	ft	ft	lb	ft lb		ft	sec	ft/sec	ft sec
II-15.1	0.36	0.0	3.5	1.3	1-2	9.87	3.2	3.1	3.4
II-15.1	0.36	0.0	3.5	1.3	1-3	22.53	6.7	3.35	3.4
II-15.1	0.36	0.0	3.5	1.3	1-4	35.40	10.5	3.0	3.4
II-15.2	0.36	0.14	3.5	0.8	1-2	9.87	3.2	3.1	3.4
II-15.2	0.36	0.14	3.5	0.8	1-3	22.53	7.0	3.2	3.4
II-15.2	0.36	0.14	3.5	0.8	1-4	35.40	10.7	3.2	3.4
II-15.3	0.36	0.29	3.5	0.25	1-2	9.87	3.1	3.2	3.4
II-15.3	0.36	0.29	3.5	0.25	1-3	22.53	6.7	3.35	3.4
II-16.1	0.24	0.0	3.5	0.9	1-2	9.87	3.7	2.7	2.7
II-16.1	0.24	0.0	3.5	0.9	1-3	22.53	8.2	2.75	2.7
II-16.1	0.24	0.0	3.5	0.9	1-4	35.40	13.1	2.6	2.7
II-16.2	0.24	0.14	3.5	0.25	. .	. .	. .	. .	. .
II-17.1	0.14	0.0	3.5	0.5	1-2	9.87	4.6	2.15	2.1
II-17.1	0.14	0.0	3.5	0.5	1-3	22.53	11.3	2.0	2.1
II-17.1	0.14	0.0	3.5	0.5	1-4	35.40	17.6	1.95	2.1
II-17.2	0.14	0.07	3.5	0.25	3-4	12.87	6.3	2.05	2.1

Table 6--Summary of periods (in seconds), Series II

Run	T_1'	T_2'	T_3'	T_4'	T_1	T_2	T_3	T_4
15.1	0.4	0.7	0.8	0.9	0.6	1.15	1.5	1.7
15.2	0.3	0.7	0.9	0.8	0.7	1.1	1.55	1.7
15.3	. .	. .	. .	. .	. .	. .	. .	. .
16.1	0.3	0.7	0.7	0.6	0.7	1.2	1.6	1.7
16.2	0.3	a	a	a	0.6	1.1	1.4	a
17.1	0.25	0.7	0.5	0.6	0.7	1.3	2.1	a
17.2	. .	. .	. .	. .	. .	. .	. .	. .
Ave.	0.31	0.7	0.73	0.73	0.66	1.17	1.63	1.7

[a] Amplitude very small; not possible to determine the time interval between crests with any degree of certainty.

Table 7--Summary of wave heights (in feet)

Series II

Run	H_1'	H_2'	H_3'	H_4'	H_1	H_2	H_3	H_4	H_1''	H_2''	H_3''	H_4''
15.1	0.019	0.008	0.006	0.006	0.019	0.012	0.018	0.006	0.0005	0.006	0.006	0.006
15.2	0.013	0.005	0.004	0.002	0.015	0.010	0.007	0.004	0.002	0.005	0.004	0.004
15.3	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .
16.1	0.026	0.012	0.006	0.004	0.031	0.014	0.008	0.006	0.021	0.011	0.006	0.002
16.2	0.003	trace	trace	trace	0.011	0.004	0.004	0.002	0.008	0.002	0.002	0.002
17.1	0.019	0.010	0.006	trace	0.019	0.008	0.007	trace	0.010	0.005	0.002	trace
17.2	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .

From an examination of the surface-time histories and the phase velocity of the initial crests, it is thought that the first wave was one of the 'Airy' type and that the following waves were dispersive. This seems to be especially true for the wave formed in the shallowest water (0.14 ft) as it can be seen to be deforming with increasing distance from the origin. This conforms with the prediction of URSELL [1953] as the parameter $HL^2/2d^3$ is in the neighborhood of thirty and hence it is not possible for a solitary wave to exist.

Dimensional analysis--In many studies of this nature it is valuable to utilize dimensional analysis to organize the variables into the smallest possible number of significant groups of parameters. Use of the π theorem of BUCKINGHAM [1915] is the usual means of obtaining this end. Two sets of dimensionless parameters were developed. One set was developed using ρ_b, g and d, and the second set was developed using ρ_b, g and T as the primary variables. An analysis of this sort is particularly valuable if it is found that certain of the paramenters are of little importance. For example, within the range of experimental conditions, it is probable that the parameter containing viscosity can be neglected. Various combinations of the dimensionless parameters were plotted to determine whether certain of the other parameters could be neglected. It was found that none could. In addition, it is known that certain of the parameters are related in such a manner that it is not possible in all cases to hold all but one constant in order to determine the individual effects.

Energy--Another approach, and one which proved more fruitful, was to consider the energy of the waves which were generated as compared with the initial potential energy (net, submerged) of the body. The potential energy (net, submerged) is the product of the net weight, submerged, of the body, and the water depth less the height of the body (0.6 ft).

An approximation of the energy contained in the waves was obtained, using the equation for the energy per wave length of a periodic train of waves of uniform small amplitude

$$E = wLH^2/8 = gwH^2\,T^2 / 16\pi \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where g is the value of gravity, w is the unit weight of water, H is the wave height (as measured from trough to crest), L is the wavelength, and T is the wave period. In the case of a disturbance of the sort being studied, this equation gives only an approximate answer. As the disturbance was found to be dispersive, it was most convenient to compute the energy from measurements close to the origin (Station 1) where the total energy was nearly concentrated in one wave. Thus the energy of the wave disturbance was considered to be given by

$$E = gw\,(H_1 + H_1'')^2\;T_1^{\,2} / 16\,\pi \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

The results are shown in Figure 9, excepting the few results of very low energy (order of magnitude of less than 10^{-3} ft lbs). It can be seen that the energy of the waves correlates rather well with the initial potential energy (net, submerged) of the body. Within the band of results, it can be seen that two general trends exist: (1) for water of constant depth, the less the initial submergence the greater the energy of the waves for a given initial potential energy of the body; (2) for constant initial depth of submergence, the smaller the water depth the greater the percentage of energy transformed into wave energy. In addition, it can be seen that the amount of energy of the wave disturbance is of the order of magnitude of one percent of the initial potential energy (net, submerged) of the vertically falling body.

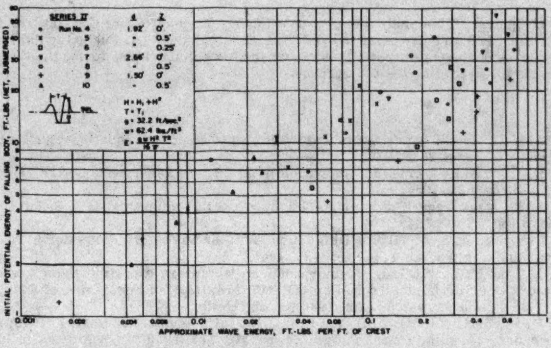


Fig. 9--Relationship between energy of wave disturbance and initial potential energy (net, submerged) of a vertically falling body

Conclusions

In general it was found that, within the range of experimental conditions, dispersive waves were generated by a body either falling vertically or sliding down an incline. An exception was the case of a flat plate falling in quite shallow water (0.1 to 0.2 foot) in which an Airy type of wave was generated, together with dispersive waves forming the tail. Surface-time histories of the disturbance measured a short distance form the source showed that a crest always formed first, followed by a trough from one to three times the amplitude of the first crest (depending upon the slope of the incline primarily), followed by a crest with about the same amplitude as the trough. Due to the dispersive qualities of the waves, additional crests and troughs continued to form with increasing distance from the origin, while at the same time the amplitudes of the initial crests and trough decreased.

The magnitudes of the amplitudes depended primarily upon the submerged weight of the body, but also upon the depth of submergence, the water depth and other characteristics of the generation.

The 'period' associated with the gravity water waves of the disturbance was found to be independent of water depth, initial depth of submergence, weight of the body, or time of the fall. It was, however, found to be related to the length of the body, with the period increasing with increasing length, and to the slope of the incline, with the smaller the incline, the greater the period.

Computations of the approximate energy of the wave disturbance generated by the vertically falling body indicated that about one per cent of the initial potential energy (net, submerged) of the body was transformed into wave energy. Within the band of results it was seen that for water of constant depth, the less the initial depth of submergence of the body, the greater the percentage of energy transformed into wave energy; and for constant initial depth of submergence, the smaller the water depth the greater the percentage of energy transformed into wave energy.

When the body was modified by adding ends to it, an entirely different type of wave was generated. It did not appear to be dispersive, but rather consisted of a single crest followed by a single trough. It belongs in the great range of $(HL^2/2d^3)$ for which there is at present no satisfactory theory.

It is interesting to note that the curves showing the correlation between the length of the body and the initial period of the waves, when extrapolated considerably, indicate that an underwater disturbance of the order of a few thousand feet in length would generate waves with an initial period of the order of 10 to 15 min. Because of the great length of such a wave, it could travel a considerable distance without being affected greatly by its dispersive qualities, because it would be traveling a short distance as measured in wave length. In fact, it would have the general appearance of the tsunamis observed in nature.

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A RELATIONSHIP BETWEEN WIND AND HEAT CHANGE OBSERVED IN A VERTICAL COLUMN OF THE SEA

C. R. Sparger

Abstract--Few satisfactory conclusions have been reached as to the influence of the atmosphere on short-term heat changes in the sea. This paper reports a simple, empirical result in this regard, the rationalization of which may prove profitable. Direct comparison has been made of certain local heat changes observed in the sea and wind stresses computed from observed velocities. Data used are those gathered by ocean-station vessels occupying COCA (52° 45′ N, 35° 30′ W) during the autumn months of 1947 and 1948.

No apparent relationship existed between the local wind stress and the heat change occurring either within the mixed layer or, separately, below the mixed layer. But there seemed to be a connection between the cumulative effect of wind stress acting during one week and the total heat-change in a 600-ft column of the sea the following week. For each year studied it was possible to find a direction such that the components of the individually observed winds in that direction varied in sign exactly as the heat-change. The directions were different for the two years. A significant correlation was found to exist between the magnitude of the appropriate component of wind stress and the heat-change, having taken the lag into account.

Introduction--Routine processing of weather-ship bathythermograph data at Texas A and M results in thermal profiles based on five-day average temperature values for all periods possible. By planimetering the area between two superimposed traces of this sort, the mid-days of the two averaging periods usually having been seven days apart, JUNG and GILCREST [1955] obtained a measure of heat-change for various periods at Station COCA. A part of these data for 1948 are used here and are listed in Table 1 as A_T.

The previous study compared A_T with the sum of the estimated heat changes due to evaporation and radiation and to the estimated dynamic effect of the wind-stress curl. Results indicated that some other influence must be important, if not paramount, in explaining A_T. Horizontal advection of heat was thought to be a likely possibility.

Currents and the spatial distribution of heat must be known in order to determine the influence of advection directly. But appropriate horizontal variations of temperature have not been measured and have not been satisfactorily estimated, nor is direct information on currents obtainable. Only through the comparatively well-known winds can something about the water movement be inferred, and the relation between the two is obscure at best.

As a first effort to deal with advection using the inadequate data available, local heat changes have been compared directly with local winds converted to stresses in a conventional way. The comparison is favorable only if a lag is introduced.

Generally eight wind observations, taken three hours apart, are made each day by weather ships occupying Station COCA. The winds are recorded in knots. Using appropriate conversion factors and the table given by SVERDRUP, JOHNSON, and FLEMING [1942, p. 491], the wind velocities have been converted to stresses expressed in [g knots/sec cm^2]. These values are assumed to be constant during a three-hour period centered on the time of observation. Multiplying by the appropriate number of seconds in each case yields a series of vectors which are assumed to represent the wind stress and its changes sufficiently well that their sum for a period of the order of a week gives the total stress effective during that week. The stresses are summed for seven-day, six-day, or three-day periods depending on the lengths of the periods of heat change with which they are to be compared. The lengths of the heat-change periods are governed by the availability of data. Directions and magnitudes of the summed stresses are listed in columns 2, 3, and 4 of Table 1.

Table 1--Summary of observed data

Wind-action period 1	Wind direction 2	Wind stress τ 3	$(\tau_K)_1$ 4	Heat-change period 5	A_T 6	Approx. heat change in mixed layer 7	Approx. heat change below mixed layer 8	K 9
		$\frac{\text{g naut mi}}{\text{sec wk cm}^2}$	$\frac{\text{g naut mi}}{\text{sec wk cm}^2}$		$\frac{\text{ft °F}}{\text{wk}}$			$\frac{\text{ft °F sec}}{\text{g naut mi}}$
1947 direction of K = 215°								
Sep. 1 - 7	217°	4.71	-4.71	Sep. 8 - 14	-150	+ 50	- 200	31.8
Sep. 8 - 14	289°	7.14	-1.97	Sep. 15 - 21	- 94	0	- 90	47.7
Sep. 15 - 21	244°	2.16	-1.89	Sep. 22 - 28	- 26	- 10	- 20	13.8
Sep. 22 - 28	146°	1.20	-0.43	Sep. 29 - Oct. 5	- 4	+150	- 150	9.3
Sep. 29 - Oct. 5	138°	4.16	-0.94	Oct. 6 - 12	- 81	-250	+ 170	86.2
1948 direction of K = 350°								
Sep. 6 - 12	284°	4.18	-1.70	Sep. 13 - 19	- 52	- 80	+ 30	30.6
Sep. 13 - 19	199°	4.74	+4.15	Sep. 20 - 26	+1664	+440	+1220	401.
Sep. 20 - 26	201°	3.36	+2.88	Sep. 27 - Oct. 3	+ 68	-220	+ 290	23.6
Sep. 27 - Oct. 3	263°	3.54	-0.18	Oct. 4 - 10	-106	+ 30	- 140	589.
Oct. 4 - 10	290°	6.85	-3.42	Oct. 11 - 17	-392	- 40	- 350	115.
Oct. 11 - 17	274°	8.61	-2.08	Oct. 18 - 24	-146	0	- 150	70.2
Oct. 18 - 24	235°	3.82	+1.62	Oct. 25 - 31	+107	-170	+ 280	66.0
Oct. 26 - 31	316°	3.60	-2.98	Nov. 2 - 7	-666	-370	- 300	223.
Oct. 31 - Nov. 6	24°	5.00	-4.14	Nov. 7 - 13	- 7	+ 40	- 50	1.7
Nov. 7 - 13	13°	4.43	-4.08	Nov. 14 - 20	-499	-330	- 170	122.
Nov. 14 - 20	254°	5.88	+0.62	Nov. 21 - 27	+276	- 20	+ 300	445.
Nov. 21 - 23	114°	2.63	+1.47	Nov. 28 - 30	+236	+100	+ 140	161.

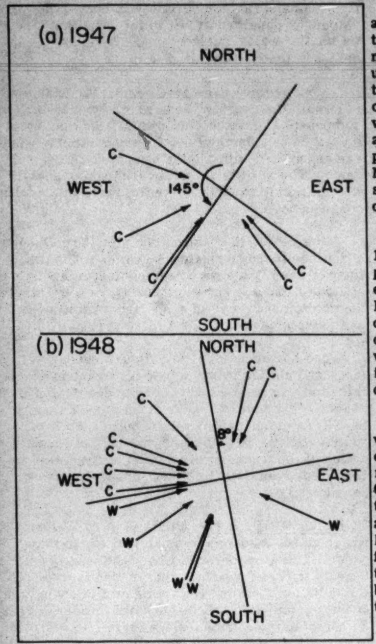

Fig. 1--Relation to wind direction and heat changes (a) 1947; (b) 1948

Data interpretation--The wind acting during a given period is compared with the heat change taking place during a period of equal length beginning seven days after the wind commences. Figure 1 demonstrates that, for observations during the autumn months of 1947 and 1948, a direction can be found such that the components of the individual winds in that direction have the same sign as the corresponding heat changes. The appropriate direction is not the same for both years. No such direction can be found, even for one season, if comparison is made with the heat change occurring simultaneously with the wind.

Not much significance can be credited to the 1947 result alone. Cooling took place during each period examined, and the wind, as computed, changed in direction through an arc of less than 180°. But both heating and cooling occurred in one or the other of the 1948 periods. It is proposed that because a direction can be found for 1948 such that wind components in that direction have the qualities described, the result is more than coincidence.

If ordered horizontal motion due to weekly winds were confined to the mixed layer, the heat change there might be expected to be more closely related to the wind than is the total heat change to 600 ft. Under such conditions, heat changes below the mixed layer should be small, being brought about by conduction or a very small scale turbulence. Such is not the case. No relation has been found between heat change in the mixed layer and the wind as computed. Furthermore, heat changes below the mixed layer are, on the whole, larger than those within (see Table 1, columns 7 and 8.)

This does not preclude the possibility that ordered horizontal motion due to weekly winds is confined to the mixed layer. But it is apparently true that appreciable horizontal water movement takes place to some point deep in the thermocline. The connection between this movement and the local winds, as computed, may not be a direct one.

In some cases the heat change in the mixed layer and that below have the same sign; equally as often they differ. It is with the algebraic sum of these changes that the wind has some relation. These facts, coupled with the apparent time-lag, are difficult to rationalize.

The conclusion is that $A_T = K(\tau_K)_1$ where A_T is proportional to the total heat change to 600 ft taking place during a several day period, and $(\tau_K)_1$ is the appropriate component of wind stress. The equation defines K. Knowledge of its physical meaning awaits theoretical advancement. Whatever the meaning, K is the magnitude of a vector having a direction which seems to be fairly persistent during part of one year, but varies from year to year. It depends heavily on horizontal gradients of temperature at all depths to 600 ft, averaged for several days. Thus, these gradients are probably relatively stable in direction. Magnitudes of K computed by the equation above are listed in Table 1, column 9.

Figure 2 is a plot of A_T vs $(\tau_K)_1$. Comparing these variables results in a linear correlation coefficient of 0.7, significant at the five per cent level. But obviously it is the direction of K alone that is stable. There is considerable variation in magnitude that is apparently not simply related to the winds. The directions in which wind components can be taken such that they vary in sign as the heat change cannot be determined by the simultaneous solution of equations of the form $A_T = K_1 \tau_x + K_2 \tau_y$ wherein successive values of A_T, τ_x, and τ_y have been inserted. There is,

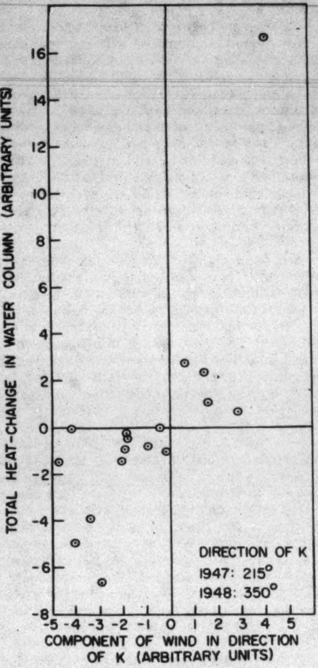

Fig. 2--Relation of A_T to $(\tau_K)_1$

first, considerable uncertainty in converting wind velocities observed at sea to the resultant stresses on the water surface. And the vector, K, is not sufficiently stable in magnitude.

Conclusions--The 1948 result, for example, is simply that weekly winds which have a northerly component are associated with a later cooling of the water to a depth of 600 ft, and southerly winds are associated with a later heating to the same depth. The results are of local meaning and are unremarkable except for the following interesting consequences.

The region in question is under the influence of the semipermanent Gulf Stream. Yet the isolines of weekly-average heat-content in a vertical column of the sea have, apparently, a very stable orientation and move in association with the average local wind.

The heat-content gradients are relatively large and change in magnitude for reasons which this study gives no clues. But the conclusion is reached that advection of heat must necessarily be taken into account in a heat budget study of such a region. In doing this, the lag between the action of the wind and the motion of the water as reflected in total vertical heat change must be considered.

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A MODIFIED-EQUATIONS METHOD FOR THE LEAST-SQUARES SOLUTION OF CONDITION EQUATIONS

L. A. Gale

Abstract--A method is developed for the adjustment of sections of a triangulation net before the data for the total adjustment are available which does not require alteration of the sectional correlate values in order to complete the total adjustment at a later date. The computational process, using Bjerhammar's solution for normal equations, leads to sectional corrections to which are added partial corrections derived from the additional equations to obtain total corrections satisfying the expanded system. The method can also be used to advantage to complete the adjustment of an expanded system of equations, the original part of which was solved by either the Gauss-Doolittle or Cholesky techniques. Two numerical examples are appended.

Introduction--The complexity of modern triangulation networks and the frequency with which sections of those nets are revised make it eminently desirable to have available an adjustment procedure which will permit initially independent adjustment of sections of the net which may then, without revision of the sectional adjustment, be incorporated into a total adjustment.

As a preliminary to the development of such a method of adjustment, the basic notation will be given, but for the methods of matrix algebra which will be employed the reader is referred to texts such as Frazer, Duncan and Collar, Elementary Matrices, or A. C. Aitken, Determinants and Matrices.

$\underset{rs}{A}$ = a matrix of order r by s

a_{ij} or $(A)_{ij}$ = element in the ith row and jth column of A

$(A)_{ii}$ = element in the principal diagonal of A

a_{in} = nth column of A

a_{ni} = nth row of A

Using matrix notation we consider the condition equations

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & & a_{1s} \\ a_{21} & a_{22} & a_{23} & & a_{2s} \\ \cdots & \cdots & \cdots & \cdots & \\ & & & & \\ & & & & \\ & & & & \\ a_{r1} & a_{r2} & a_{r3} & \cdots & a_{rs} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ \cdot \\ \cdot \\ \cdot \\ v_s \end{bmatrix} = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ \cdot \\ \cdot \\ \cdot \\ w_r \end{bmatrix}$$

or

$$\underset{rs}{A}\ \underset{s1}{V} = \underset{r1}{W} \qquad \ldots\ldots\ldots\ldots \tag{1}$$

where V represents the corrections to be determined; W, the absolute terms of the equations; and $r < s$.

There is an infinite number of solutions for these equations. However, we want that solution which makes the sum of the squares of the v's a minimum, that is,

$$\underset{1s}{V'}\,\underset{s1}{V} = \text{a minimum} \tag{2}$$

The solution of (1), when the least-squares condition is applied, is given by **BJERHAMMAR** [1951] as

$$\underset{s1}{V} = \underset{sr}{A'}\,(\underset{rs}{A}\,\underset{sr}{A'})^{-1}\,\underset{r1}{W} \tag{3}$$

Substituting

$$\underset{r1}{K} = (\underset{rs}{A}\,\underset{sr}{A'})^{-1}\,\underset{r1}{W} \tag{4}$$

in (3) we get

$$\underset{s1}{V} = \underset{sr}{A'}\,\underset{r1}{K} \tag{5}$$

where K represents the correlates and A' corresponds to the usual correlate sheet.

When (4) is written in the form

$$(A\,A')\,K = W \tag{6}$$

we have the normal equations as derived from (1). Note that (A A') is a symmetrical matrix the elements of which correspond to the detached coefficients of the K's in the normal equations.

The solution for V can be considered in two stages: (1) solving (6) to get K; and (2) using K in (5) to obtain V.

Since (A A') is a symmetrical matrix we replace it by the symbol S. Thus we have the normal equations

$$SK = W \tag{7}$$

and their solution

$$K = S^{-1}W \tag{8}$$

Bjerhammar's method for the solution of normal equations--To develop a convenient method for computing S^{-1}, we use triangular matrices.

A symmetrical matrix can be written as the product of two triangular matrices each of which is the transpose of the other. Thus, we have

$$T'\,T = S \tag{9}$$

where T is of the form $\begin{bmatrix} t_{11} & t_{12} & t_{13} \\ 0 & t_{22} & t_{23} \\ 0 & 0 & t_{33} \end{bmatrix}$ and S is of the form $\begin{bmatrix} s_{11} & s_{12} & s_{13} \\ s_{12} & s_{22} & s_{23} \\ s_{13} & s_{23} & s_{33} \end{bmatrix}$

Also

$$(T'\,T)^{-1} = T^{-1}\,T'^{-1} = S^{-1} \tag{10}$$

where T^{-1} is of the form $\begin{bmatrix} d_{11} & d_{12} & d_{13} \\ 0 & d_{22} & d_{23} \\ 0 & 0 & d_{33} \end{bmatrix}$

and $(T^{-1})' = T'^{-1}$

From (9) we obtain

$$T = T'^{-1}\,S \tag{11}$$

From (11), we get an expression for the nth column of the primary T matrix

$$t_{in} = T'^{-1}s_{in} \tag{12}$$

By definition we have

$$T^{-1}T = I \tag{13}$$

For the nth column of the unit matrix we can write

$$\underset{nn}{T^{-1}}\ t_{in} = I_{in} \quad \ldots\ldots\ldots\ldots\ldots\ldots (14)$$

from which we get, with $i = 1, 2, 3, \ldots\ldots, (n-1)$

$$\underset{(n-1)(n-1)}{T^{-1}}\ t_{in} + d_{in}\ t_{nn} = \left\{0\right\} \ldots\ldots\ldots\ldots\ldots\ldots (15)$$

From (12) we get

$$t_{in} = \underset{(n-1)(n-1)}{T'^{-1}}\ s_{in}$$

Thus (15) can be written as

$$\underset{(n-1)(n-1)}{T^{-1}}\ \underset{(n-1)(n-1)}{T'^{-1}} s_{in} + d_{in}\ t_{nn} = \left\{0\right\}$$

or

$$d_{in}\ t_{nn} = \underset{(n-1)(n-1)}{-S^{-1}}\ s_{in} \ldots\ldots\ldots\ldots\ldots\ldots (16)$$

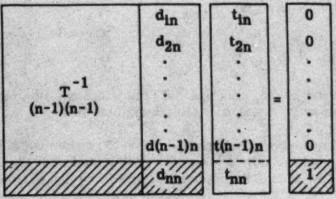

Fig. 1--Sketch illustrating derivation of Eq. 15

In (15) the $\underset{nn}{T^{-1}}$ matrix has been reduced to order $(n-1)\times(n-1)$. Therefore the column $d_{in}\ t_{nn}$ must be included to make the equation valid.

At this point, Bjerhammar introduces a triangular matrix which is derived by dividing each column of the reciprocal T^{-1} matrix by its diagonal element, and an orthogonal matrix whose diagonal elements are identical with the elements of the principal diagonal in the reciprocal T^{-1} matrix.

The triangular matrix is denoted by ∇^{-1} and its transpose, $(\nabla^{-1})'$ by Δ^{-1}.

Note that the diagonal elements of both these matrices are equal to unity.

The orthogonal matrix is denoted by $\phi^{0.5}$, where $(\phi^{0.5})_{ii} = (T^{-1})_{ii}$, and $(\phi^{0.5})_{ij} = 0$ when $i \neq j$.

Thus, we have

$$\nabla^{-1}\ \phi^{0.5} = T^{-1}, \text{ and } \phi^{0.5}\ \Delta^{-1} = T'^{-1} \quad \ldots\ldots\ldots\ldots\ldots (17)$$

With the help of (10) and (17) we obtain

$$S^{-1} = \nabla^{-1}\phi^{0.5}\phi^{0.5}\ \Delta^{-1} = \nabla^{-1}\ \phi\ \Delta^{-1} \quad \ldots\ldots\ldots\ldots\ldots (18)$$

Using $t_{nn} = (\phi^{0.5})_{nn}$, we derive from (12) the relation

$$(\phi^{-0.5})_{nn} = (\phi^{0.5})_{nn}\ \Delta^{-1} s_{in},$$

or

$$(\phi^{-1})_{nn} = \underset{nn}{\Delta^{-1}}\ s_{in} \quad \ldots\ldots\ldots\ldots\ldots\ldots (19)$$

From (16) and (18) is derived an expression for the nth column of ∇^{-1}, namely

$$\nabla^{-1}_{in} = -\nabla^{-1}\ \phi\ \Delta^{-1} s_{in} \ldots\ldots\ldots\ldots\ldots\ldots (20)$$

where the matrices on the right hand side are of order $(n-1)\times(n-1)$ and i has the successive values $1, 2, 3 \ldots\ldots (n-1)$.

The solution of the normal equations given in (8) can now be written as

$$K = \nabla^{-1}\phi\ \Delta^{-1} W \ldots\ldots\ldots\ldots\ldots\ldots (21)$$

Bjerhammar's application of (19) and (20) to the solution of normal equations is illustrated in the scheme of elimination given subsequently under The Procedures for Bjerhammar's Solution.

New, progressive solution using Bjerhammar's method of elimination for normal equations--Using Bjerhammar's solution for K in (3) we get

$$V = A' \nabla^{-1} \emptyset \Delta^{-1} W \quad . . . . (22)$$

If we regard $\emptyset \Delta^{-1} W$ as modified correlates and denote them by M to distinguish them from the conventional correlates and $A' \nabla^{-1}$ as a modified correlate sheet, a new method of solution is indicated, and the solution can be written as

$$V = A' \nabla^{-1} M$$

This procedure is equivalent to modifying the original condition equations, then forming the normal equations from which the modified correlates are obtained. The modified condition equations are given by

$$\Delta^{-1} AV = \Delta^{-1} W$$

and the normal equations by

$$\Delta^{-1} AA' \nabla^{-1} M = \Delta^{-1} W$$

which reduces to

$$\emptyset^{-1} M = \Delta^{-1} W \quad . . . . (23)$$

Because $\emptyset^{-1}$ is orthogonal, that is, each equation in (23) contains only one unknown, obtaining values for the individual M's is a simple matter, when $\emptyset^{-1}$ and Δ^{-1} have been obtained.

Now Bjerhammar's solution contains M and the modifying matrix Δ^{-1} (see Procedures, subsequently). Therefore, we need only compute the modified correlate sheet $A' \nabla^{-1}$ and with M, already determined, calculate V. The usual K (last row of Bjerhammar's solution) are not computed.

Since Bjerhammar's elimination proceeds by rows, it is possible to obtain successive columns of the modified correlate sheet together with the corresponding M's. We have here a progressive type of solution, that is, at any stage of an adjustment, the v's determined from the first p columns will satisfy the first p condition equations, and the correlates already determined are not altered by the subsequent condition equations.

The advantages of this 'Progressive solution' are: (1) The correlates are obtained in forward order. (2) The subsequent addition of condition equations to the original system requires only the computation of a like number of columns in the modified correlate sheet as well as the corresponding correlates from which partial v's are computed. These partial v's are added to the original ones to obtain v's which satisfy the expanded system. (3) Differential adjustments are simplified. (4) When the condition equations can be suitably arranged, independently adjusted sections of a system of condition equations can be combined in a relatively simple manner (see next paragraph). (5) The method can be used to advantage when condition equations are added to a system previously adjusted by either the Gauss-Doolittle or Cholesky Methods. The original solution is retained and partial v's obtained by means of the progressive method are added to the original v's to get a solution for the expanded system.

Partitioning of adjustments using the progressive method of solution--If the condition equations can be arranged so that the coefficients of the v's produce a partitioned matrix of the form shown in (24) below, v's can first be determined for the independent sections. To these 'sectional' v's are added the partial v's obtained from the 'uniting equations' to obtain the complete solution.

The condition equations are arranged to give the form

$$\begin{bmatrix} \underset{mt}{A} & \underset{mu}{0} \\ \underset{nt}{0} & \underset{nu}{B} \\ \underset{pt}{a} & \underset{pu}{b} \end{bmatrix} \underset{s}{V} = \begin{bmatrix} \underset{m\,1}{W}_{A} \\ \underset{n\,1}{W}_{B} \\ \underset{p\,1}{W}_{C} \end{bmatrix} \quad . . . . (24)$$

where $m + n + p = r$ $\qquad m < t$

$t + u = s$ $\qquad n < u$

$r < s$ $\qquad$ and $\quad p < u$

$p < t$

The corresponding normal equations are

$$\begin{bmatrix} \underset{mm}{AA'} & \underset{mn}{0} & \underset{mp}{Aa'} \\ \underset{nm}{0} & \underset{nn}{BB'} & \underset{np}{Bb'} \\ \underset{pm}{aA'} & \underset{pn}{bB'} & \underset{pp}{(aa' + bb')} \end{bmatrix} \underset{r1}{K} = \begin{bmatrix} W_A \\ W_B \\ W_C \end{bmatrix}$$

From $[AA' \;\; Aa'] \; K = W_A$, the first independent section, we get V_A which satisfies $[A \;\; 0] \; V_A = W_A$. From $[BB' \;\; Bb'] \; K = W_B$, the second independent section, we get V_B which satisfies $[0 \;\; B] \; V_B = W_B$. From $[aA' \;\; bB'/(aa' + bb')] \; K = W_C$, we derive V_C with the help of appropriate elements in the eliminations of the independent sections. For the complete adjustment, $V = V_A + V_B + V_C$.

To obtain two or more independent sections in the adjustment of a triangulation net when corrections are applied to the observed directions, two methods of arranging the condition equations are suggested.

(1) (a) The equations for all the figures to one side of the 'partitioning quadrilateral' are written.
(b) The equations for all the figures to the opposite side of the 'partitioning quadrilateral' are written next.
(c) Finally, the four equations for the 'partitioning quadrilateral' are written.
To combine the independent sections, we obtain the v's, (V_C), from four rows in the elimination and four columns of the modified correlate sheet, and add the V_C to the v's of the independent sections.

(2) When the configuration of two adjacent quadrilaterals is such that the poles of the side equations can be placed at the opposite ends of the common line, the equations can be so arranged that the computation of the 'combining' v's, (V_C), requires only two rows in the elimination and two columns in the modified correlate sheet. In Figure 2 ABCD and CDEF are the adjacent quadrilaterals.

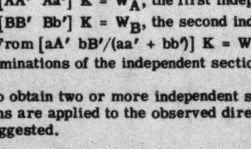

Fig. 2--Sketch showing adjacent quadrilaterals

(a) Equations for all the figures to the left of the quadrilateral ABCD and angle equations for the shaded triangles ABC and ABD as well as a side equation for ABCD, with the pole at C, are written.

(b) Angle equations for the shaded triangles CEF and DEF, a side equation for CDEF with the pole at D, and all the equations for the remaining figures to the right of EF are written.

(c) The two previously omitted angle equations, one from each of the quadrilaterals ABCD and CDEF are written last.

In either of the above methods, any other equations which involve corrections to directions on both sides of the partition, for example, length, azimuth, latitude and longitude equations, are included in the last group. The number of independent sections in an adjustment depends on the number of figures in a net, the nature of these figures, as well as the number of equations desired in each section.

Use of the progressive method when condition equations are added to a system previously adjusted by either the Gauss-Doolittle or Cholesky methods--It can be shown that each row of the Gauss-Doolittle elimination which eliminates a K is a row of the $-\phi \, \Delta^{-1} S$ and $\phi \, \Delta^{-1} W$ matrices in Bjerhammar's elimination. Thus, it is possible to derive the ∇^{-1} matrix (see Eq. (20) and Bjerhammar's scheme of elimination), for the system of equations previously adjusted by the Gauss-Doolittle method. The partial v's for the added equations are then derived by the progressive method and added to the v's of the original adjustment to get the v's for the expanded system. A numerical example is given at the end of this paper.

It can also be shown that when each row of the Cholesky elimination is divided by the negative reciprocal of its leading term we get the $-\phi\,\Delta^{-1}S$ and $\phi\,\Delta^{-1}W = M$ matrices.

The procedures for Bjerhammar's solution of normal equations and the 'progressive solution' for v's are explained below for a system of three condition equations containing five v's.

A--Condition equations

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \\ v_5 \end{bmatrix} = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix}$$

B--Correlate sheet

	K_1 = (41)	K_2 = (42)	K_3 = (43)
v_1	a_{11}	a_{21}	a_{31}
v_2	a_{12}	a_{22}	a_{32}
v_3	a_{13}	a_{23}	a_{33}
v_4	a_{14}	a_{24}	a_{34}
v_5	a_{15}	a_{25}	a_{35}

C--Normal equations

K_1	K_2	K_3	-w	Check
11	12	13	14	15
. .	22	23	24	25
. .	. .	33	34	35

D--Bjerhammar's scheme of elimination

(11)	1	(12)	(13)	(14)	(15)
(22)	(21)	1	(23)	(24)	(25)
(33)	(31)	(32)	1	(34)	(35)
. .	(41)	(42)	(43)	1	. .

The solution as represented in table D consists of

$$\begin{bmatrix} (11) \\ (22) \\ (33) \end{bmatrix} = (\phi)_{ii} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{see Eq. (19)}$$

$$\text{where} \qquad (\phi)_{ii} = (\phi^{-1})^{-1}_{ii}$$

$$\begin{bmatrix} 1 & 0 & 0 \\ (21) & 1 & 0 \\ (31) & (32) & 1 \end{bmatrix} = \Delta^{-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{see Eq. (20)}$$

$$\begin{bmatrix} -1 & (12) & (13) \\ 0 & -1 & (23) \\ 0 & 0 & -1 \end{bmatrix} = -\phi\,\Delta^{-1}S$$

$$\begin{bmatrix} (14) \\ (24) \\ (34) \end{bmatrix} = \emptyset\, \Delta^{-1} W$$

$$\{ (41) \quad (42) \quad (43) \} = K = \nabla^{-1} \emptyset\, \Delta^{-1} W \text{ . . . . see Eq. (21)}$$

The elements of the solution are derived in successive rows as follows:

(11) = -1/11
(12) = (11)12
(13) = (11)13
(14) = (11)14
(15) = (11)15

(21) = (12)
(22) = -1/[(21)12 + 22]
(23) = (22) [(21)13 + 23]
(24) = (22) [(21)14 + 24]
(25) = (22) [(21)15 + 25]

(32) = (23)
(31) = (32) (12) + (13)
(33) = -1/[(31)13 + (32)23 + 33]
(34) = (33) [(31)14 + (32)24 + 34]
(35) = (33) [(31)15 + (32)25 + 35]

(43) = (34)
(42) = (43) (23) + (24)
(41) = (43) (13) + (42) (12) + (14)

Checks for rows to the right of the principal diagonal

(12) + (13) + (14) - 1 = (15)
(23) + (24) - 1 = (25)
(34) - 1 = (35)

Checks for individual elements to the left of the principal diagonal

(31) = (21) (23) + (13)
(42) = (32) (34) + (24)
(41) = (31) (34) + (21) (24) + (14)

The progressive solution is as follows. The elements in the modified correlate sheet, Table E, are computed from Table B and Table D, excepting the last row of Table D which is not computed when this method is used:

E--Modified correlate sheet

	M_1 = (14)	M_2 = (24)	M_3 = (34)
v_1	a_{11}	$a_{11}(21) + a_{21}$	$a_{11}(31) + a_{21}(32) + a_{31}$
v_2	a_{12}	$a_{12}(21) + a_{22}$	$a_{12}(31) + a_{22}(32) + a_{32}$
v_3	a_{13}	$a_{13}(21) + a_{23}$	$a_{13}(31) + a_{23}(32) + a_{33}$
v_4	a_{14}	$a_{14}(21) + a_{24}$	$a_{14}(31) + a_{24}(32 + a_{34}$
v_5	a_{15}	$a_{15}(21) + a_{25}$	$a_{15}(31) + a_{25}(32) + a_{35}$

Numerical example of a partitioned adjustment--For the adjustment of the net of two quadrilaterals in Figure 3 the 'partitioning' line is 3-4. The condition equations are written in the following order.

$$(1.3) - (1.2) + (2.1) - (2.3) + (3.2) - (3.1) + 0.553 = 0$$

$$(1.4) - (1.2) + (2.1) - (2.4) + (4.2) - (4.1) + 2.764 = 0$$

$$+0.14(1.2) - 2.74(1.3) + 2.60(1.4) + 1.45(2.1) + 2.28(2.3) - 3.73(2.4) - 1.97(3.1) + 0.37(3.2) + 1.60(3.4) + 6.26 = 0$$

$$(3.5) - (3.6) + (5.6) - (5.3) + (6.3) - (6.5) - 2.307 = 0$$

$$(4.5) - (4.6) + (5.6) - (5.4) + (6.4) - (6.5) - 0.661 = 0$$

$$-2.57(4.3) - 1.17(4.5) + 3.74(4.6) + 2.04(5.3) - 0.30(5.4) - 1.74(5.6) - 1.41(6.3) + 3.22(6.4) - 1.81(6.5) + 2.78 = 0$$

$$(2.4) - (2.3) + (3.2) - (3.4) + (4.3) - (4.2) - 3.212 = 0$$

$$(3.4) - (3.5) + (4.5) - (4.3) + (5.3) - (5.4) + 2.226 = 0$$

where the notation (1.2) denotes the correction to the direction from 1 to 2.

Correlate sheet

	1	2	3	4	5	6	7	8
(1.2)	-1	-1	+0.14					
(1.3)	+1		-2.74					
(1.4)		+1	+2.60					
(2.1)	+1	+1	+1.45					
(2.3)	-1		+2.28				-1	
(2.4)		-1	-3.73				+1	
(3.1)	-1		-1.97					
(3.2)	+1		+0.37				+1	
(3.4)			+1.60				-1	+1
(4.1)		-1						
(4.2)		+1					-1	
(3.5)				+1				
(3.6)				-1				
(4.3)						-2.57	+1	-1
(4.5)					+1	-1.17		+1
(4.6)					-1	+3.74		
(5.3)				-1		+2.04		+1
(5.4)					-1	-0.30		-1
(5.6)				+1	+1	-1.74		
(6.3)				+1		-1.41		
(6.4)					+1	+3.22		
(6.5)				-1	-1	-1.81		

Normal equations

1	2	3	4	5	6	7	8	W
+6.00	+2.00	-1.37				+2.00		+0.553
	+6.00	+7.64				-2.00		+2.764
		+42.0788				-7.24	+1.60	+6.26
			+6.00	+2.00	-3.38		-2.00	-2.307
				+6.00	-1.32		+2.00	-0.661
					+44.8732	-2.57	+3.74	+2.78
						+6.00	-2.00	-3.212
							+6.00	+2.226

First independent elimination

$(\phi)_{ii}$	1	2	3	7	8	M
-0.166667	+1	-0.33333	+0.22833	-0.33333		-0.09217
-0.1875	-0.33333	+1	-1.51813	+0.50000		-0.48369
-0.033928	+0.73437	-1.51813	+1	+0.09279	-0.05428	-0.08380

Second independent elimination

$(\phi)_{ii}$	4	5	6	7	8	M
-0.166667	+1	-0.33333	+0.56333		+0.33333	+0.38450
-0.1875	-0.33333	+1	+0.03625		-0.50000	-0.02025
-0.0232763	+0.55125	+0.03625	+1	+0.05982	-0.06307	-0.03455

Numerical example--The progressive method is used in the following pages to complete the adjustment of a net part of which was previously adjusted by the Gauss-Doolittle method.

(a) The Doolittle method is used to adjust the quadrilateral 1234 of Figure 3. The v's are entered in the V_A column of the correlate sheet.

(b) The progressive method is used to obtain the v's in the column V_B.

(c) The v's in the column $V = V_A + V_B$ are the final corrections to the observed directions for the complete net.

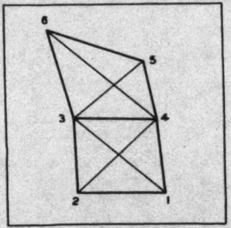

Fig. 3--Sketch to illustrate adjustment

Final

$(\phi)_{ii}$	1	2	3	4
-0.278357	-0.43185	+0.35913	+0.09279	+0.03298
-0.339241	-0.24294	+0.25128	-0.01064	+0.48074

Modified correlate

V	M	1	2	3	V_A
		-0.09217	-0.48369	-0.08380	
(1.2)	+0.38101	-1	-0.66667	+0.92376	+0.33722
(1.3)	-0.08020	+1	-0.33333	-2.00563	+0.23713
(1.4)	-0.30080		+1	+1.08187	-0.57435
(2.1)	-0.43887	+1	+0.66667	+0.66624	-0.47046
(2.3)	-0.34758	-1	+0.33333	+1.54563	-0.19858
(2.4)	+0.78646		-1	-2.21187	+0.66904
(3.1)	+0.25164	-1	+0.33333	-2.70437	+0.15757
(3.2)	+0.25113	+1	-0.33333	+1.10437	-0.02349
(3.4)	-0.61616			+1.60000	-0.13408
(4.1)	+0.20617		-1	+1.51813	+0.35647
(4.2)	-0.65070		+1	-1.51813	-0.35647
(3.5)	+0.44750				
(3.6)	-0.33411				
(4.3)	+0.55999				
(4.5)	-0.07603				
(4.6)	-0.03943				
(5.3)	-0.44915				
(5.4)	+0.07721				
(5.6)	+0.37193				
(6.3)	+0.33525				
(6.4)	+0.03382				
(6.5)	-0.36907				

V	K	Correlate sheet								
		1	2	3	4	V_A	5	6	7	8
		-0.10738	-0.27300	+0.49447	-0.03349					
(1.2)	+0.38098	-1	-1			+0.38038				
(1.3)	-0.07764	+1				- 0.10738				
(1.4)	-0.30333		+1			-0.27300				
(2.1)	-0.43889	+1	+1		+1.76	-0.43932				
(2.3)	-0.33468	-1		-1	-0.31	-0.37671				
(2.4)	+0.78358		-1	+1	-1.45	+0.81603				
(3.1)	+0.24876	-1			-5.20	+0.28153				
(3.2)	+0.24860	+1		+1	+3.23	+0.27892				
(3.4)	-0.61504			-1	+1.97	-0.56045	+1	+1		+2.77
(3.5)	+0.44441						-1		+1	-3.14
(3.6)	-0.32672							-1	-1	+0.37
(4.1)	+0.20889		-1		+2.87	+0.17688				
(4.2)	-0.64833		+1	-1	-2.66	-0.67839				
(4.3)	+0.57177			+1	-0.21	+0.50150	-1	-1		+1.17
(4.5)	-0.06513						+1			+2.26
(4.6)	-0.06721							+1		-3.43
(5.3)	-0.45609						+1		-1	
(5.4)	+0.07354						-1			
(5.6)	+0.38255								+1	
(6.3)	-0.33483							+1	+1	+1.81
(6.4)	+0.02755							-1		-7.23
(6.5)	-0.36238								-1	+5.42

elimination

5	6	7	8	M
+0.00217	+0.05982	+1	+0.47026	+0.49785
-0.50127	-0.03494	+0.47026	+1	-0.11339

sheet

4	5	6	V_B	7	8	V_C
+0.38450	-0.02025	-0.03455		+0.49785	-0.11339	
				+0.08571	-0.00983	+0.04379
				-0.68609	-0.21379	-0.31733
				+0.60038	+0.22362	+0.27354
				+0.06183	-0.00709	+0.03159
				-0.35659	-0.25158	-0.14900
				+0.29476	+0.25867	+0.11742
				+0.24905	+0.26390	+0.09407
				+0.60248	+0.22338	+0.27462
				-0.85154	+0.51272	-0.48208
				-0.35913	-0.25128	-0.15030
				-0.64087	-0.21898	-0.29423
+1	-0.33333	+0.55125	+0.37220	+0.03298	-0.51926	+0.07530
-1	+0.33333	-0.55125	-0.37220	-0.03298	-0.48074	+0.03809
		-2.57000	+0.08879	+0.84626	-0.43994	+0.47120
	+1	-1.13375	+0.01892	-0.06782	+0.53961	-0.09495
	-1	+3.70375	-0.10771	+0.22156	+0.37059	+0.06828
-1	+0.33333	+1.48875	-0.44269	+0.08905	+0.44798	-0.00646
	-1	-0.33625	+0.03186	-0.02012	-0.48825	+0.04535
+1	+0.66667	-1.15250	+0.41082	-0.06894	+0.04027	-0.03889
+1	-0.33333	-0.85875	+0.42092	-0.05137	+0.53001	-0.08567
	+1	+3.25625	-0.13275	+0.19479	-0.61378	+0.16657
-1	-0.66667	-2.39750	-0.28817	-0.14342	+0.08477	-0.08090

Modified correlate sheet				
5	6	7	8	V_B
-0.23290	+0.14053	+0.37600	+0.00372	
-0.00792	-0.00633		-0.09577	+0.00060
-0.22992	-0.18403		+0.55092	+0.02974
+0.23784	+0.19036		-0.45515	-0.03033
-0.00570	-0.00456		-0.06909	+0.00043
-0.26025	-0.20827		+0.18398	+0.03203
+0.26595	+0.21284		-0.11489	-0.03246
+0.27017	+0.21622		-0.06384	-0.03277
+0.23765	+0.19020		-0.45749	-0.03032
+0.49218	+0.39391		+1.25945	-0.05459
-1.00000	+0.19968	+0.50000	-1.22406	+0.44441
	-1.00000	-0.50000	+0.48594	-0.32672
-0.26005	-0.20813		+0.18632	+0.03201
-0.23414	-0.18739		+0.49987	+0.03006
-0.50580	-0.40480		+2.51569	-0.07027
+1.00000	-0.19968	+0.50000	+2.10406	-0.06513
	+1.00000	-0.50000	-5.30594	-0.06721
+1.00000	-0.19968	-0.50000	-1.91594	-0.45609
-1.00000	+0.19968	-0.50000	+0.15594	+0.07354
		+1.00000	+1.76000	+0.38255
	+1.00000	+0.50000	+1.69406	+0.33483
	-1.00000	+0.50000	-5.35406	+0.02755
		-1.00000	+3.66000	-0.36238

Original normal equations				Subsequent normal equations				
1	2	3	4	5	6	7	8	-w
+6.00	+2.00	+2.00	+10.50					+0.553
	+6.00	-2.00	-2.32					+2.764
		+6.00	+2.57	-2.00	-2.00		-1.60	-3.212
			+62.0066	+2.18	+2.18		+5.2112	+1.30
				+6.00	+2.00	-2.00	+7.00	+2.226
					+6.00	+2.00	+6.84	+0.620
						+6.00	-7.12	-2.307
							+120.8362	+4.03

Doolittle solution for K's for the first four normal equations

$(\emptyset)_{ii}$	K_1	K_2	K_3	K_4	Abst.T.
	+6.00	+2.00	+2.00	+10.50	+0.553
-0.166667	-1.00	−0.33333	-0.33333	[illegible].75000	-0.09217
		+6.00	-2.00	-2.32	+2.764
		-0.66667	-0.66667	-3.50000	-0.18433
		+5.33333	-2.66667	-5.82000	+2.57967
-0.187500		-1.00	+0.50000	+1.09125	-0.48369
			+6.00	+2.57	-3.212
			-0.66667	-3.50000	-0.18433
			-1.33333	-2.91000	+1.28984
			+4.00000	-3.84000	-2.10649
-0.25			-1.00	+0.96000	+0.52662
				+62.0066	+1.30
				-18.37500	-0.96775
				- 6.35108	+2.81506
				- 3.68640	-2.02223
				+33.59412	+1.12508
-0.0297671				- 1.00	-0.03349

Back solution

K_1	K_2	K_3	K_4
-0.09217	-0.43869	+0.52662	-0.03349
+0.05861	-0.03655	-0.03215	-0.03349
-0.16482	+0.24724	0.49447	
+0.09100	-0.27300		
-0.10738			

Progressive solution used to obtain the modified correlate columns and M

$(\emptyset)_{ii}$	1	2	3	4	5	6	7	8	M
-0.25	-0.50000	+0.50000	+1	+0.96000	+0.50000	+0.50000		+0.40000	
-0.0297671	-2.59375	+1.57125	+0.96000	+1	-0.00774	-0.00774		-0.10[illegible]40	
-0.200081	-0.22992	+0.23784	+0.49257	-0.00774	+1	+0.19968	+0.40016	-1.23481	-0.23290
-0.208390	-0.18403	+0.19036	+0.39422	-0.00619	-0.19968	+1	-0.50000	-0.99594	+0.14053
-0.250000					+0.50000	-0.50000	+1	+1.76000	+0.37600
-0.0105237	+0.55092	-0.45515	-0.70586	-0.09367	-0.15594	-1.87594	+1.76000	+1	+0.00372

Note: The first two rows are omitted since they do not enter into the solution.

Reference

BJERHAMMAR, ARNE, Applications of calculus of matrices to method of least squares, with special reference to geodetic calculations, Trans. R. Inst. Tech., Stockholm, no. 49, 1951.

Geodetic Survey of Canada
Ottawa, Canada

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DEVELOPMENT AND SIGNIFICANCE OF SEEPAGE STEPS IN SLOPE EROSION

R. F. Hadley and B. N. Rolfe

Abstract--This study offers an hypothesis, based on field and laboratory data, for the development of one type of erosional scarplets on hillslopes in the semiarid Great Plains. The scarplets are crescent-shaped and are generally less than two feet in height. They have four integral parts: (1) tread, (2) seepage face, (3) base, and (4) debris-slope. Mapping shows that these features are developed roughly parallel to the stream channels and in some cases follow a slope continuously nearly on contour for as much as a quarter of a mile.

The scarplets are developed in surficial mantle material overlying a fine-grained, weathered bedrock surface. Infiltration tests show that a zone of relatively low permeability exists at the contact between the surficial mantle and the weathered bedrock which causes a seepage of subsurface flow wherever the contact is exposed on a free face. These features have been called seepage steps by the authors. After a step is initiated it migrates upslope nearly on contour.

Particle-size analyses of soil samples taken in seepage steps do not reveal large differences in the texture of the material of the tread and base; but the surficial material, which is mainly alluvium and colluvium, is made more permeable by transport.

X-ray studies of the mineral constituents in soil samples show that downslope migration of soil material is a fundamental part of step formation. Very young soil profiles in a semiarid region may acquire the characteristics of a more mature soil by the erosional processes involved in seepage-step formation. Seepage-step studies emphasize the significance of subsurface hydrology in slope development and soil formation.

Introduction

The study of the development and significance of erosional features and the hydraulics involved in the formation of those of aqueous origin have long held the interest of geologists and engineers. Observational data on rates of gully growth and extent of physical damage caused by other erosional processes are abundant in the literature. However, a fundamental explanation of how a particular erosional feature develops on a land surface is frequently lacking in published material dealing with the broad subject of erosion. Quantitative field measurements and analysis of minor erosional features by the geomorphologist may contribute, in some degree, to the solution of complex problems of land erosion in critically eroding areas.

The present study offers an hypothesis, based on field and laboratory data, for the development and continuing growth of one type of erosional scarplets on hillslopes in the semiarid Great Plains. Evidence is presented also on the type of soil-profile development that may result from the erosional processes involved.

Many upland slopes in the Great Plains physiographic province in eastern Wyoming and western South Dakota and Nebraska are broken by erosional scarplets, generally less than two feet in height (see Fig. 1). These scarplets are arcuate or crescent shaped in general outline and are concave downslope. Mapping shows that these features are roughly parallel to the stream channels and in some places follow a slope continuously almost on contour for as much as a quarter of a mile. However, they occur most commonly as short, unconnected segments measuring a few hundred feet along the perimeter. The scarplets may be present at either the foot of a slope near the axis of the valley or close to the crest of the hill, and frequently several occupy the same slope in stairstep fashion. These features have been named seepage steps by the authors.

These seepage steps are best developed on hillslopes having gradients of less than ten per cent, although they have been observed on slopes as steep as 15 to 18 pct. On slopes steeper than 18 pct, however, the surface is usually broken by rills and gullies; whereas on gently sloping interfluves and bottomlands the erosion is predominantly in the form of sheet wash.

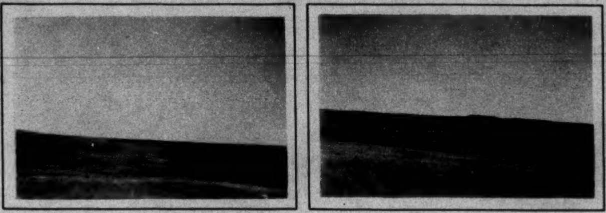

Fig. 1--Photographs of typical seepage-step topography in sec. 15, T 36 N, R 63 W, Niobrara County, Wyoming

Previous investigations

Others have described erosional features in the Great Plains which are similar to those called seepage steps. RUBEY [1928] describes crescent-shaped scarps which he states are a result of ground sinking and sliding by removal of the fine material. SHARPE [1938] speaks of 'stepped crescents' found in parts of the Great Plains from Texas to Montana and commonly attributed to effects of sheet wash and overgrazing. He also believes that soil creep plays an important role in the formation of these 'shallow crescentic scars.' BENNETT [1939, p. 281] states that the process is a combination of downslope flowage of soil beneath sod and vertical downsinking of the surface immediately within the crescent. THORP [1945] speaks of 'cat-steps' resulting from the uphill recession of gully walls in loess and loessial soils in Nebraska. From the description given by Thorp, cat-steps are evidently similar in physical appearance to seepage steps, but occurring in localities of thick loess deposits, the hydraulics of their development must be quite different.

The objective of this study is to define more clearly, by detailed field mapping, infiltration tests, and laboratory analysis of soil samples, the erosional processes responsible for seepage-step features.

Methods and procedures

Field work--General field studies dealing with the erosional characteristics of the Cheyenne River basin were begun in 1949. During the course of the field work it was noted that seepage steps constituted the principal erosional breaks on many upland slopes. In several isolated watersheds seepage steps have dissected slopes so severely that they present a serious erosion problem. Therefore, these preliminary observations led to a more detailed study of these features during the summers of 1952 and 1953 in an effort to gain a clearer understanding of this type of erosion on relatively uniform slopes.

Seepage-step topography is prominently displayed in the drainage basin of Crazy Woman Creek, Niobrara County, Wyoming. A detailed topographic map of a selected small area (approximately 35 acres) was completed using a contour interval of two feet and a horizontal scale of 1:1200 to bring all slope irregularities and seepage-step characteristics sharply into focus. The selected area lies in the NW 1/4 sec. 15, T 36 N, R 63 W (see Fig. 2). In addition to the mapping, several measurements were made of gradients both above and below seepage-step scarplets at widely scattered points in the Cheyenne River basin.

Height of steps, density of vegetation, and texture of the surficial mantle material were examined at several seepage-step sites to determine if there is any consistency in the relationship of these factors in step development.

Infiltration tests were made in the field using double-ring infiltrometers. These tests were run to determine if a zone of relatively low permeability exists at the base of the seepage step.

Soil samples were taken both above and below seepage-step scarplets in the mapped area to determine the textural and mineralogical changes, if any, resulting from this type of erosion.

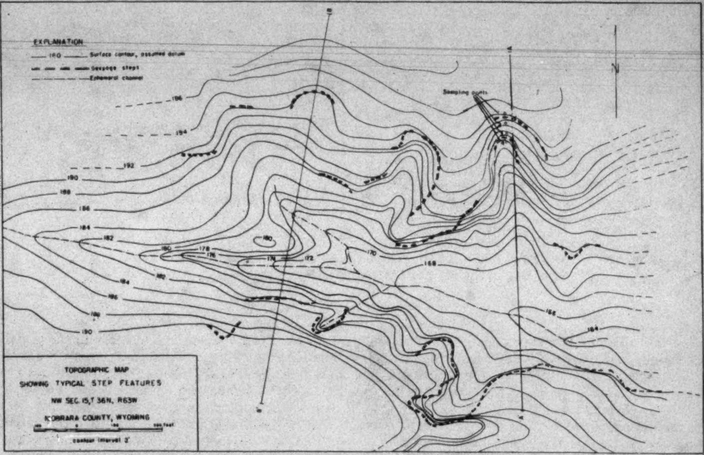
EXPLANATION
180 Surface contour, assumed datum
Seepage steps
Ephemeral channel
Sampling points
N
196
194
192
190
188
186
184
182
180
178
176
174
172
170
168
166
164
TOPOGRAPHIC MAP
SHOWING TYPICAL STEP FEATURES
NW SEC. 15, T 36N, R63W
NIOBRARA COUNTY, WYOMING
0
100
feet
contour interval 2'

Fig. 2--Topographic map showing typical step features, NW 1/4 sec. 15, T 36 N, R 63 W, Niobrara County, Wyoming

Laboratory procedure--Particle-size analyses were made of 16 soil samples taken in the mapped area. An examination of the mineral content in the silt and clay fractions of each sample was made in the laboratory.

The soils were treated according to the procedure described by TRUOG and Others [1936]. The pH was determined in a 1:1 soil paste with a Beckman pH meter, and the calcium carbonate ($CaCO_3$) content by reaction with 0.1 NHCl. The silt and clay fractions were studied with copper Ka radiation using a Norelco Geiger-counter x-ray spectrometer. Differential cation treatment and glycerol solvation described by WALKER [1949] were used to distinguish the various minerals. The results of these analyses and the discussion of their bearing on seepage-step erosion appear elsewhere in this paper.

Description and classification

There are four integral elements in a typical seepage step: (1) the tread, or slope segment upslope from the scarplet; (2) the seepage face, or actively eroding scarplet face; (3) the base, which is the exposed surface of the relatively impermeable layer, at the base of the seepage face; and (4) the debris slope, or area of waste accumulation downslope from the step. These elements are shown diagrammatically in Figure 3.

The tread generally represents the profile of the hillslope before the steps have developed, except in cases where there is a succession of seepage steps with one eroding upslope into the debris fan of another. In the case of slopes broken by a single step, it is assumed that the slope can be reconstructed in a downhill direction from the tread, as in Figure 3, in order to visualize surface conditions prior to step development.

The seepage face is the key element of the actively eroding seepage step. It is initiated at the point on a hillslope where shallow subsurface flow crops out at the surface and saturates the surficial mantle. This wetting action loosens the soil and makes it readily available for removal by surface flow. The opportunity for a seepage face to develop is best near the axis of the valley where the valley alluvium may be trenched by a channel or gully. Seepage steps have been observed, however, which began some distance up the slope where a layer of relatively impermeable material intersects

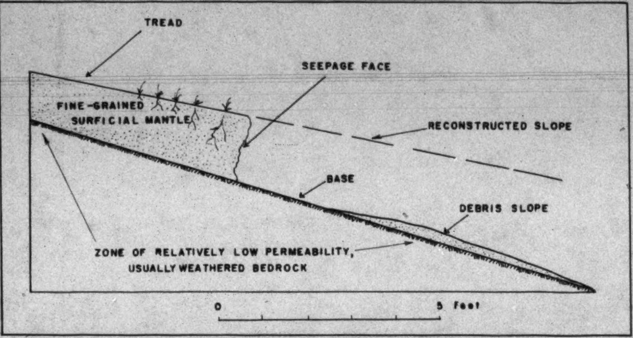
TREAD
SEEPAGE FACE
FINE-GRAINED SURFICIAL MANTLE
RECONSTRUCTED SLOPE
BASE
DEBRIS SLOPE
ZONE OF RELATIVELY LOW PERMEABILITY, USUALLY WEATHERED BEDROCK
0
5 feet

Fig. 3--Diagram of typical seepage step showing integral parts

the surface profile of the slope. The seepage face migrates up a slope as the seepage loosens the material and surface flow transports the soil down the slope. In the area studied the height of the seepage face is generally controlled by the thickness of the surficial mantle overlying the weathered bedrock, which is approximately two feet.

The base is the line of contact between the surficial mantle and the zone of relatively low permeability which is exposed at the bottom of the seepage face. This zone of low permeability is generally a weathered bedrock surface. The area of exposure of the base is generally quite small because the material eroded from the face is deposited over the base on the debris slope. Uphill from the seepage face the base is covered by the surficial mantle.

The debris slope, which is the area of accumulation of eroded material below the seepage face, is generally slightly convex and fan-shaped. Seepage-step features are of such relatively minor proportions, however, that the debris fan does not markedly change the slope profile (Fig. 4). Also, each additional period of storm runoff tends to grade the deposits of previous storms and to transport fine material farther downslope.

The tread, seepage face, base, and debris slope are distinguishable in every well-developed seepage step. It is necessary, however, to make some distinction between seepage steps occurring as a single feature on a hillslope and those which occur as a part of a wave of several scarps. The authors have distinguished the two types as: (1) single, and (2) multiple seepage steps. The single step either occupies a hillslope as a lone feature or is the farthest one upslope in a sequence. The seepage face is eroding headward in undisturbed surficial material and a soil profile of the tread represents a modal soil profile in the parent material. The multiple seepage step is downslope from the single step and is eroding headward into the debris material derived from erosion upslope (see Fig. 5). The erosional process is undoubtedly the same in both instances, but the character of the material beneath the treads of the two steps is markedly different.

Rainfall characteristics--The average annual precipitation is 14 to 16 inches in the portion of the Great Plains where seepage steps have been observed by the writers. Well-developed step features might well occur in areas of either higher or lower rainfall.

In more arid regions of Wyoming, New Mexico, and Arizona where the average annual rainfall is less than ten inches, seepage steps are absent as distinguishable erosional features. This is probably best explained by the fact that a large percentage of the precipitation in these areas comes as short, violent storms which result in very little soil saturation. Similarly, in more humid regions where the soil is at field capacity most of the time within a very slight depth below the surface, seepage-step development may occur in a minute and obscure manner. We have no observational data, however, to substantiate these inferences, and discussion of seepage-step phenomena in regions outside the semiarid Great Plains is beyond the scope of this paper.

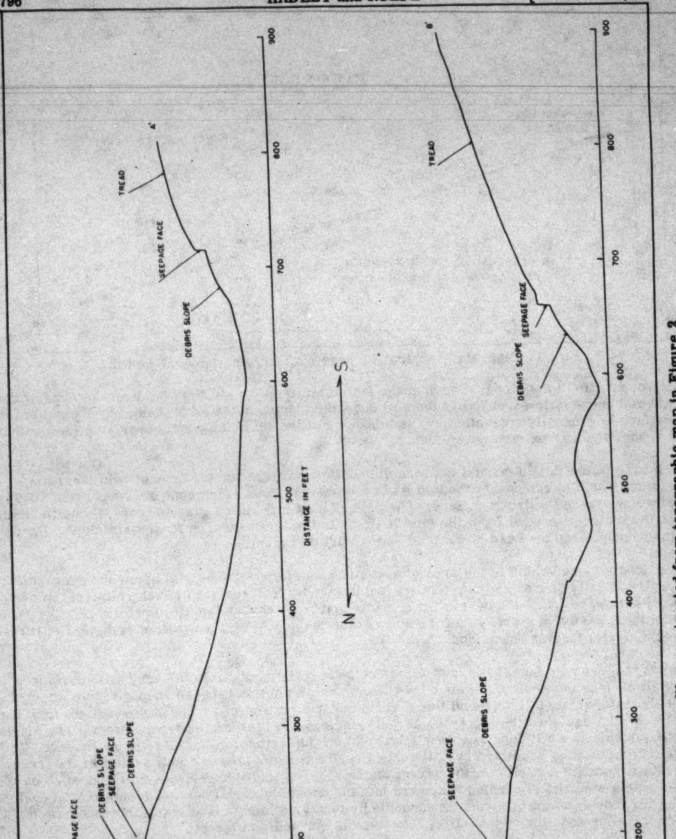

Fig. 4--Valley profiles constructed from topographic map in Figure 2

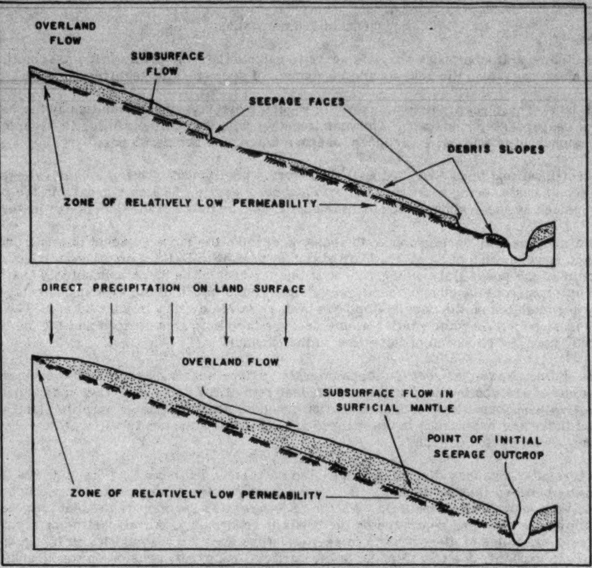
OVERLAND FLOW
SUBSURFACE FLOW
SEEPAGE FACES
DEBRIS SLOPES
ZONE OF RELATIVELY LOW PERMEABILITY
DIRECT PRECIPITATION ON LAND SURFACE
OVERLAND FLOW
SUBSURFACE FLOW IN SURFICIAL MANTLE
POINT OF INITIAL SEEPAGE OUTCROP
ZONE OF RELATIVELY LOW PERMEABILITY

Fig. 5--Illustrations showing concept of seepage-step development on a uniform hillslope; (a) uniform hillslope showing movement of subsurface flow before formation of seepage step; (b) same hillslope after development of single seepage step in surficial mantle and multiple seepage step in debris material

Slope requirements--Degree of slope and slope length vary greatly in upland areas of the Cheyenne River basin. Uniform slopes of eight to ten per cent and slope lengths of 500 to 1000 ft are most common. However, in areas that are badly dissected by gullies and rills, upland slopes as steep as 60 pct have been measured by the authors, the maximum slope lengths being less than 250 ft. Seepage-step features are best developed on upland slopes that are generally quite uniform and free of major erosional scars. From field measurements that have been made, there seems to be a definite relation between degree of slope and seepage-step characteristics. Slope length also may be an important factor, but many slopes are occupied by several steps in succession, thus obscuring the effect of slope length.

The disposal of precipitation falling on a land surface is dependent to a large extent on the degree of slope. Slopes of less than ten per cent generally allow sufficient infiltration of precipitation to initiate seepage-step erosion. Gentler slopes - from two to three per cent - reduce the erosive power of surface flow considerably and erosion is confined principally to sheet wash. Steeper slopes, up to 15 to 18 pct, may show formation of seepage steps. Still steeper slopes - 18 to 20 pct - are generally broken by rills and gullies and the velocity of surface runoff is sufficiently high to keep infiltration at a minimum. Regardless of the slope, however, the density of the vegetative cover and the texture of the soil material must be considered in a study of seepage steps.

All seepage-step slopes described in this paper occur in soil material composed predominantly of silt- and clay-size particles. The soils have developed on fine-textured shales of Late Cretaceous age and have shallow, lithosolic profiles. The parent rock lies close to the surface and this condition is apparently very conducive to step formation.

Genesis and mechanics

Field studies and laboratory analysis serve to substantiate the preliminary assumptions that have been made regarding the genesis and mechanics of seepage-step features.

Field data--The topographic map shown in Figure 2 displays diagrammatically the fundamental features of seepage-step landscape. The map, together with the valley profiles in Figure 4, aids in defining the characteristics of land slopes, seepage faces, and debris slopes.

The profiles along lines A-A′ and B-B′ in Figure 4 are typical of many upland valleys in the Cheyenne River basin, being relatively uniform and quite gentle. The only breaks in the profiles are those caused by the seepage steps and the small, convex bulge of the debris-fan material.

When a seepage step develops near the base of a slope, the slope segment downhill from the seepage face is very often quite steep. For example, in profile B-B′, a seepage step has developed near the base of the south slope on a gradient of ten per cent. The slope undoubtedly has been steepened by erosion of the channel during flood flow. Also, much of the eroded material which ordinarily accumulates on the debris slope has been removed by flow in the channel. The gradient of the debris slope will become gentler as the seepage face migrates upslope and the debris material is deposited above the elevation of flood flow in the channel.

Figure 2 also shows that seepage steps migrate upslope nearly on contour lines. In many instances the steps are continuous for several hundred feet at the same elevation under conditions of comparatively uniform slope. Also, short, unconnected scarp segments may lie along a single contour and there are indications in the mapped area that these segments will eventually unite into a continuous seepage-step scarplet.

Slope irregularities may disrupt seepage-step movement as shown by Figure 2. On the north slope, midway between lines A-A′ and B-B′, a long, arcuate step is terminated abruptly at the topographic nose near the southeast tip. Another seepage-step segment is present approximately 60 ft downslope, but they are separated by the break in topography. An inspection of Figure 2 will reveal several examples of discontinuity in seepage steps due to irregularities in topography. The discontinuity is probably due to a thinning of the surficial mantle by erosion on topographic highs.

The departure from a smooth profile caused by a seepage step and the accumulated fan of debris material varies slightly at different positions on a slope. In profile A-A′ of Figure 4 the steps on the north side of the valley occupy a slope having a gradient of 8.5 pct, whereas on the south side of the valley a seepage step is developed on a slope of 5.5 pct. The seepage faces on the steeper slope are approximately one foot high and the debris slopes are inconspicuous. On the gentler slopes the seepage face is two feet high and the debris material has built a fan which makes a noticeable bulge on the profile. It is possible that these variations exist because of differences in the thickness of the permeable surficial mantle and also differences in velocity of surface runoff. The seepage faces on the steeper slopes are probably smaller because any precipitation falling on the slope is carried away as surface runoff too quickly to allow an appreciable depth of infiltration. Also, the velocity of the surface runoff would be great enough to transport eroded material farther downslope and obliterate the alluvial fan. Sheet erosion may also reduce the thickness of the surficial mantle more on the steeper slopes, thus reducing the height of the seepage face. Conversely, on the gentler slope the surficial mantle is thicker, which may explain the higher seepage face on the south slope. In addition, lower velocities of surface runoff also prevent removal of eroded material from below the seepage face and allow a well-defined debris fan to accumulate.

Several stakes were placed on slopes occupied by seepage steps in June 1953 in order to measure the rate of upslope movement of seepage faces. These observation sections were remeasured in October 1954 and the average rate of headward erosion during the 17-month period was 0.5 foot. The years 1953 and 1954 were abnormally dry in eastern Wyoming, and the observed rates of seepage-step movement are probably lower than the long-term average.

Infiltration tests--The hypothesis of seepage-step development depends primarily on the existence of a zone of impaired permeability at the base of the seepage face. To test this hypothesis, a series of infiltration tests was run in the field using double-ring infiltrometers. The outer ring is 12 inches and the inner ring is six inches in diameter. Both rings are filled with water in order to maintain a constant head of water in the inner ring where the intake of water is measured. The ring-infiltrometer tests were run in six locations on the tread and on the base of seepage-step features. The average results of a series of four tests run on seepage steps occurring in the Pierre shale and in soils derived from the shale appear in Figure 6.

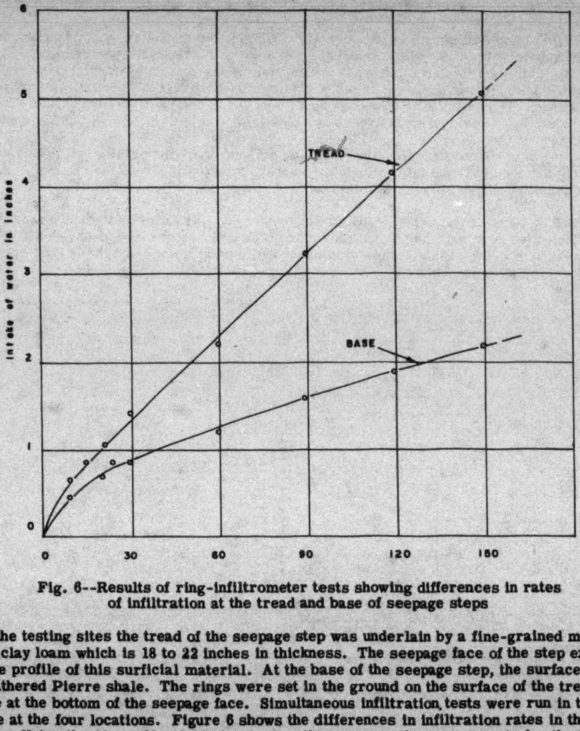

Fig. 6--Results of ring-infiltrometer tests showing differences in rates of infiltration at the tread and base of seepage steps

At the testing sites the tread of the seepage step was underlain by a fine-grained mantle of silt and clay loam which is 18 to 22 inches in thickness. The seepage face of the step exposed a complete profile of this surficial material. At the base of the seepage step, the surface exposed was weathered Pierre shale. The rings were set in the ground on the surface of the tread and in the base at the bottom of the seepage face. Simultaneous infiltration tests were run in the tread and base at the four locations. Figure 6 shows the differences in infiltration rates in the tread and base. Using the 40- to 60-minute interval on the curve as the average rate for the first hour, the intake of water is 0.70 inch/hour in the tread and 0.23 inch/hour on the base for seepage steps in the Pierre shale and soils derived from the shale. Tests made in other geologic formations displaying step topography show similar differences in infiltration rates. In steps in the Fort Union formation and soils derived from it, the intake was 0.50 inch/hour in the tread and 0.20 inch/hour in the base. In the White River formation the rates were 0.90 inch/hour in the tread and 0.20 inch/hour in the base. These data show that the existence of a zone of relatively low permeability apparently exists at the base of seepage-step features developed on different lithologic types throughout the Cheyenne River basin. It was found that areas of well-developed seepage-step topography generally had a surficial mantle approximately two to three feet thick overlying less permeable weathered bedrock. This condition is common on hillslopes in semiarid regions where low rainfall has prevented the accumulation of a thick surficial mantle. Where the weathered bedrock in the base is fine-grained and relatively impermeable, the conditions are right for seepage-step development.

Four composite soil samples were taken at comparable depths from each of four profile sites. Their location is shown on the topographic map (Fig. 2) near the north end of profile line A-A'.

Point 1 is the tread of a single seepage step and lies immediately upslope from the seepage face. Point 2 is the base of the same step and lies immediately downslope from the seepage face. The single seepage step lies near the crest of a hill and is approaching the culmination of its upslope migration. Points 3 and 4 represent the tread and base, respectively, of a multiple seepage step downslope from the preceding single step.

The multiple step represents replication of the single step except for the disturbed, transported nature of the surficial mantle. The subsurface hydrology that was effective in producing the single step is equally active in the development of the multiple step. The soil material overlying the Pierre shale in the multiple seepage step is a winnowed counterpart of the surficial soil material in the single step. The resultant rudimentary soil profiles of the multiple step treads are therefore not residual but a residual-transported combination.

Laboratory data--Laboratory analyses include particle-size distribution, pH determinations, calcium carbonate content, and mineralogical composition of the 0.020-0.002 mm and <0.002 mm size fractions. Discussion of the data follows.

Figures 7 to 10 are cumulative-frequency curves of the soil material in the 16 samples. To facilitate discussion of these data the quartile diameters were determined at the 25 and 75 pct lines on the cumulative curves. Table 1 shows the quartile diameter values and the coefficients of sorting in the four sampling profiles.

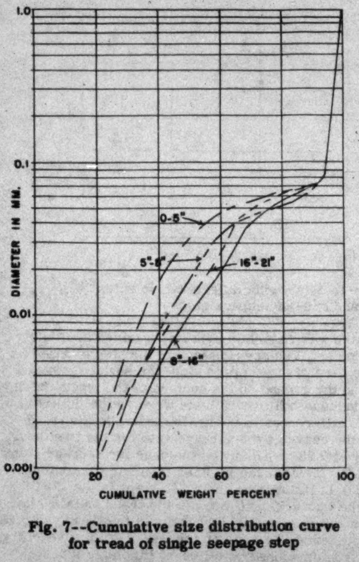

Fig. 7--Cumulative size distribution curve for tread of single seepage step

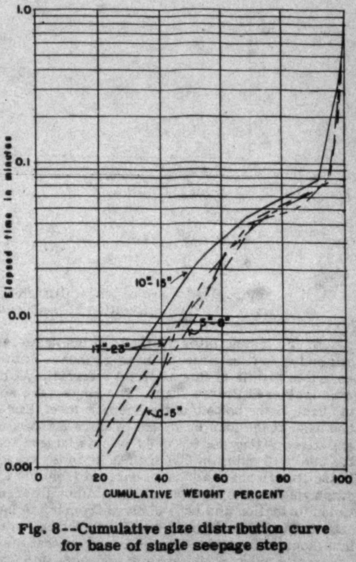

Fig. 8--Cumulative size distribution curve for base of single seepage step

Considering first the single seepage step, Table 1 shows that there is very little difference in Q_1 values for the tread and the base. The same relation is true for Q_3 values. The mean value for Q_3 is 0.047 mm for the base in contrast to 0.053 mm for the tread. This indicates that the mobile part of the seepage-face material lies in the silt range.

Comparison now of the quartile diameter relations in single and multiple steps reveals a shift toward the coarser side in the multiple. All median diameter values are smaller in the samples of the single steps. There has been a compression of the over-all size spread in the multiple steps,

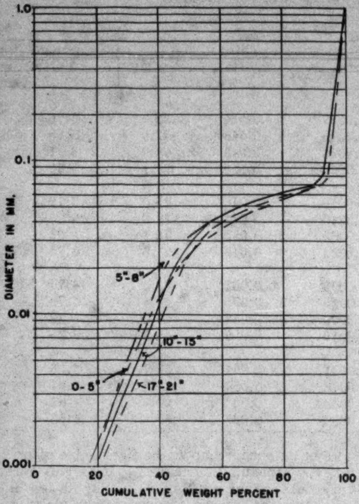

Fig. 9--Cumulative size distribution curve for tread of multiple seepage step

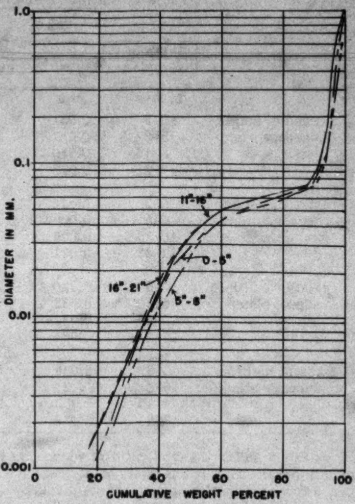

Fig. 10--Cumulative size distribution curve for base of multiple seepage step

the Q_3/Q_1 ratios being larger in the single units. Thus, the geomorphological process has effected a gradual increase in content of coarser particles, the greatest change occurring between the clay and silt sizes.

The coefficient of sorting expresses the measure of the average quartile spread [TRASK, 1932]. It is expressed as $\sqrt{Q_3/Q_1}$. Trask states that if the coefficient of sorting is greater than 4.5 the sediment is poorly sorted. The computed values in Table 1 show that all samples analyzed in this study can be classed as poorly sorted. The sorting coefficients, however, have lower values in the multiple step indicating better sorting in a downhill direction as the material is winnowed by transportation.

The particle-size analyses do not reveal large differences in the texture of the soil material of the tread and base of seepage-step features. This is undoubtedly due to the homogeneity of the Pierre shale and soils derived from the shale. However, the surficial material, which is mainly an alluvial and colluvial mantle on a weathered bedrock surface, is made more permeable by transport as shown by the infiltration tests.

The results of the x-ray diffraction analyses of the 0.020-0.002 mm and <0.002 mm size fractions are shown in Figure 11. The data in Figure 11a indicate that there is little difference in the 0.020-0.002 mm size separates as to kind and amounts of minerals present. Apparently, there has been no mineralogical sorting of this separate during step formation.

Figure 11b pictures the kind and relative amounts of minerals present in the <0.002 mm size fractions. By regarding the base of the multiple step as the oldest soil material and the tread of the single step as the youngest, one may summate the mineralogical winnowing of these fines during step formation. Vermiculite is present in the single tread but decreases in amount toward the multiple base. Quartz occurs moderately in the single tread but has been winnowed appreciably toward the older base. This may be attributed to its chemically unreactive nature and consequent response to transport only as a function of its low fall velocity. The montmorillonoid or swelling

Table 1--Statistical summary of textural relationships

Location	Depth of sample	Median $\bar{M}$	First quartile Q_1	Third quartile Q_3	Q_3/Q_1	Sorting $So = \sqrt{Q_3/Q_1}$
	inches	mm				
Tread of single seepage step	0-5	0.031	0.0027	0.060	22.2	4.70
	5-8	0.017	0.0015	0.048	32.0	5.65
	8-16	0.010	0.0010	0.048	48.0	6.91
	16-21	0.013	0.0020	0.056	28.1	5.30
Base of single seepage step	0-5	0.012	0.0010	0.045	45.0	6.70
	5-8	0.0086	0.0015	0.043	28.6	5.35
	10-15	0.019	0.0032	0.052	16.3	4.03
	17-23	0.011	0.0022	0.048	21.8	4.77
Tread of multiple seepage step	0-5	0.026	0.0023	0.052	22.6	4.75
	5-8	0.032	0.0025	0.056	22.4	4.73
	10-15	0.031	0.0020	0.058	29.0	5.39
	17-21	0.031	0.0016	0.055	34.3	5.85
Base of multiple seepage step	0-5	0.028	0.0021	0.054	25.7	5.08
	5-8	0.023	0.0018	0.057	31.6	5.61
	11-16	0.033	0.0030	0.062	20.7	4.53
	16-21	0.033	0.0030	0.062	20.7	4.53

clay has not suffered any significant winnowing in spite of its occurrence as the finest-size discrete clay mineral. This is due to its highly reactive nature and probable flocculation in the highly calcareous medium. Mica maintains its dominance throughout the four profiles, reflecting its lesser response to chemical environment as well as resistance to slope transport because of its platy morphology. The kaolin trends are too indecisive for comment. Feldspar, although chemically unreactive, apparently is more resistant to transport than quartz. This may be due to characteristic shape of the minerals, particles of fresh feldspar having sharp, angular cleavage, whereas quartz has none.

From the preceding data it appears that swelling-type clay minerals (montmorillonoids) are not as mobile in flocculent soil environments as would be presumed from their fine discrete size. It is also apparent that the shape factor of minerals must be considered along with size when evaluating erosion potential. The contrast in activity of the mica and vermiculite minerals is worthy of further study. Future research by the authors will explore the interrelationship of mineralogy, chemical environment, and geomorphology.

The pH and the $CaCO_3$ content of the various horizons are shown diagrammatically in Figure 12. The absence of any significant difference in $CaCO_3$ content reflects the semiarid climate. There has been too little carbonated water associated with step formation to effect leaching, save for the slight reduction that has taken place in the surface horizon of the single tread, probably as a result of the presence of a better vegetative cover. The pH values all lie within the range expected in calcareous soils and, without additional information on the kind and amount of salts present, further interpretation would be invalid.

Relation of the problem to soil formation--Downslope migration of soil material is a fundamental part of step formation. Surficial material is continually moved downslope as the seepage steps proceed uphill. The accumulation of debris from the eroding face of the step results in a surficial mantle of transported soil material that has been winnowed of its fines. In this way very young soil profiles in the semiarid region may acquire the characteristics of a more mature soil. Instead of a shallow surface horizon, such a soil may acquire a weathered mantle of about two feet. The resultant soil profile may be considered polygenetic in that two soil origins are represented in the profile. NIKIFOROFF [1949] has described such soils as 'cumulative.'

Geomorphic and pedologic implications

With the field evidence thus far assembled, supported by data from laboratory analyses, certain geomorphic and pedologic implications may be inferred for seepage-step features. Although

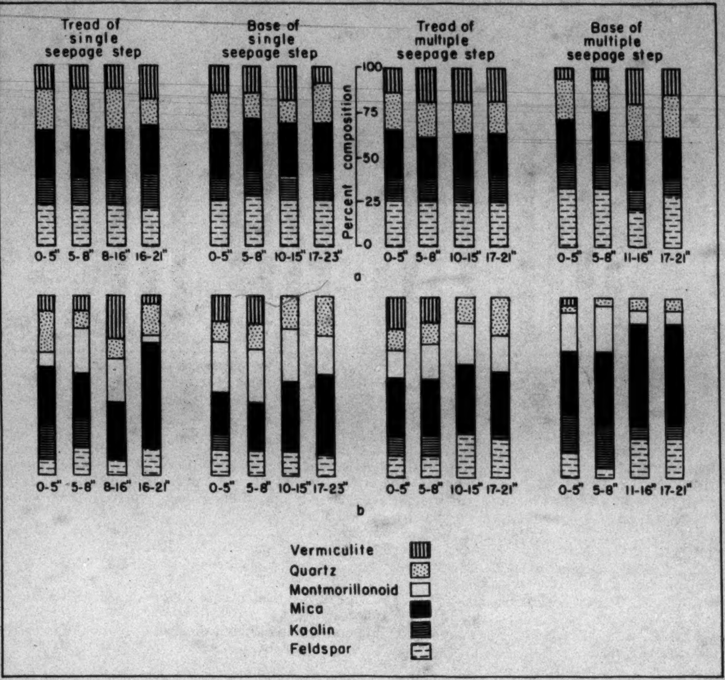

Fig. 11--X-ray diffraction data: relative amounts of minerals present in the (a) 0.020-0.002 mm size fractions at the depths indicated, and (b) <0.002 mm size fractions at the depths indicated

the data are restricted to the areas of field study, some implications of a general nature will be presented.

(1) If seepage-step erosion is a continuing process on the type of slopes which have been studied, and it appears to be, it may be a primary factor in retreat of slopes and rounding of topography. The authors expect to study this further.

(2) The slope of the land surface controls the height of the seepage face, owing primarily to the fact that steeper slopes generally have thinner surficial mantles as a result of more intense erosion.

(3) Seepage-step studies have emphasized the significance of subsurface hydrology in geomorphological processes and soil formation.

(4) A condition of marked differential permeability within a soil profile with the lower horizons being more impermeable may lead to a seepage force, thereby constituting an environment for step formation if a free face is developed.

(5) Seepage steps may occur in humid regions, but it is likely that the time-intensity factor and geomorphic expression may be quite different.

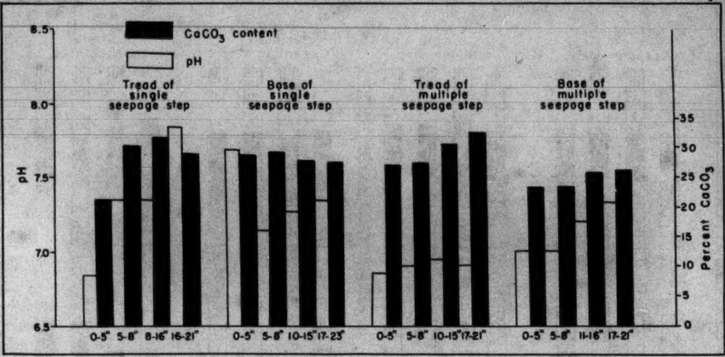

Fig. 12--Content of $CaCO_3$ in per cent and pH at depths indicated; pH determined from 1:1 paste using Beckman glass electrode pH meter; per cent $CaCO_3$ determined gravimetrically using 0.1 NHCl

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EFFECT OF CURRENT DROUGHT UPON WATER SUPPLIES IN CEDAR CITY VALLEY, UTAH

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Abstract--The ground water in the pumping district in Cedar City Valley, Utah, is considered by the Utah State Engineer to be fully appropriated, and he has not authorized drilling of irrigation wells there since 1942, except as replacements for wells having established rights. In spite of this regulation, the water levels in representative wells in 1954 were the lowest of record, and four to ten feet lower than the minima recorded during the drought of the 1930's. This recession is attributed in large part to the current drought in the southwestern United States. In the five years ended October 1, 1954, precipitation at Cedar City was markedly less than in any other five-year period in the past 50 years, and stream runoff was likewise far below average. Ground-water withdrawal has exceeded replenishment in these drought years, but it cannot yet be concluded that the ground-water resources are overdeveloped in the sense that pumpage exceeds the long-term average replenishment to the reservoir.

Introduction--Drought in an arid region is different in many respects from drought in a humid region. A few rainless weeks during the growing season are enough to create drought in the humid eastern half of the country, and the Easterner regards the arid parts of the West, where rainless periods may be measured in months, as areas of permanent or perennial drought.

To the Westerner, however, several months without rain do not constitute a drought. He recognizes this as the normal climate of the region, where precipitation is characteristically inadequate for cultivated crops, and where therefore the basic water supplies for agriculture, as well as for industrial and public use, are obtained from streams and reservoirs, springs and wells. To him, drought is not apparent until these supplies of surface water or ground water are reduced.

Nevertheless, deficiency in precipitation is a basic factor in drought, in the West as in the East. The Westerner may be less concerned with the rain that falls upon his crops during the growing season, but he is more concerned with precipitation throughout the year and precipitation in the areas from which his surface- or ground-water supplies are derived.

Droughts in the West are measured in years, or even in decades. The current drought began as early as 1942 in some parts of the Southwest. The effects of drought upon surface water are readily apparent in reduced streamflow and reservoir storage. Reductions in spring flow may also be ascribed to drought in areas where there is no possibility that the reduction has been caused by withdrawals from wells. It is very difficult, however, to discriminate the effects of drought upon the major ground-water reservoirs of the Southwest. In most valleys there has been a progressive lowering of water levels in wells in recent years. Part of this may be a direct effect of drought, a product of reduced recharge. Part may be an indirect effect of drought, resulting from increasing the rate of pumping or the length of pumping season in order to supplement failing stream or reservoir supplies.

In some areas, the pumping from wells has been in excess of replenishment for many years, and water levels in wells have declined significantly. In recent years the rate of lowering may have been augmented somewhat by drought, but pumping has been the chief cause of the decline. And in other areas new wells have been drilled to provide water for rapidly increased population, additional irrigated acreage, or new industries. Water levels in wells in these areas have declined chiefly because of this increased use of water.

The effects of drought upon ground-water supplies can best be evaluated in areas where there has been little increase in development in recent years. CUSHMAN and HALPENNY [1955] have discussed the effects of drought in Safford Valley, Ariz., where irrigated acreage has not expanded because of natural limitations. This paper describes the effects of drought in Cedar City Valley, Utah, where State regulation prevents development of new irrigation wells.

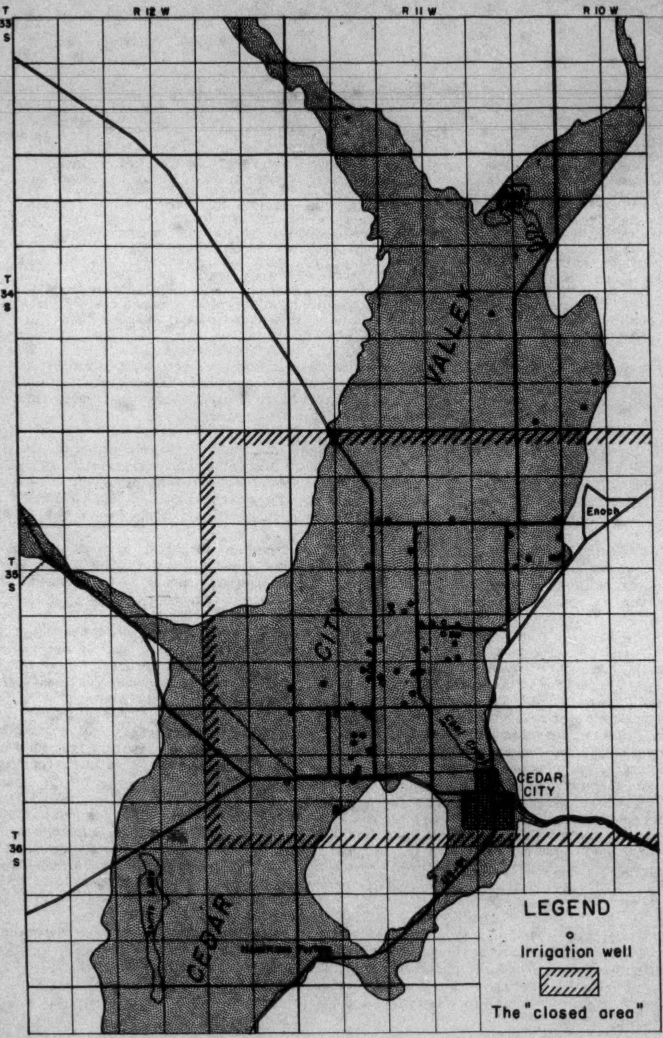
T 33 S
R 12 W
R 11 W
R 10 W
T 34 S
T 35 S
T 36 S
CEDAR CITY VALLEY
Enoch
CEDAR CITY
LEGEND
○ Irrigation well
▨ The "closed area"

Fig. 1--Map of Cedar City Valley, Utah, showing location of irrigation wells, and the 'closed area'

Cedar City Valley (Fig. 1) is in southwestern Utah, about 250 miles southwest of Salt Lake City. Physiographically it is at the eastern edge of the Great Basin; it is bordered on the east by the Kolob Plateau, a unit of the Colorado Plateaus, which reaches elevations 5000 ft higher than the valley floor. Structurally, Cedar City Valley is in the Hurricane Fault zone: some faults have formed escarpments along the valley borders, and others have displaced the alluvial sediments that underlie the valley floor to undetermined depths. The water supplies of Cedar City Valley, both surface water and ground water, are derived principally from Coal Creek, which rises in the high plateau country and enters the valley at Cedar City. No streams leave the valley, but negligible quantities of ground water move northwestward through Iron Springs Gap and Twentymile Gap into Escalante Valley. Practically all the water from tributary streams and from precipitation in Cedar City Valley is discharged by evapotranspiration within the valley. The geology and hydrology of the valley have been described by THOMAS and TAYLOR [1946].

The ground-water reservoir--As in most of the valleys of the Great Basin, the valley fill in Cedar City Valley is made up of irregular and lenticular beds of clay, silt, sand, and gravel, deposited chiefly by Coal Creek and to a lesser extent by other tributary streams, and locally reworked by lake or wind action. The materials generally are poorly sorted, but there are some beds of well-sorted material.

Ground water is obtained chiefly from the gravel and sand in this fill. Beds of clay and silt give rise to artesian conditions over a large part of Cedar City Valley, particularly in the lower northern half and in the southwestern part. The confining layers responsible for artesian pressure are evidently discontinuous and act chiefly as minor baffles to the free circulation of ground water. Some of the faults that cross the valley fill also act as barriers to ground-water circulation.

More than 200 wells are now in use in Cedar City Valley, of which about 150 are domestic and stock-watering wells, including several that flow by artesian pressure. The aggregate discharge from these wells constitutes a very small proportion of the total draft upon the ground-water reservoir. The predominant use of ground water in the valley is for irrigation. As shown on Figure 1, there are about 70 pumped irrigation wells in Cedar City Valley, and generally 60 or more of these are in operation every year.

On the basis of available data, the Utah State Engineer has concluded that all ground water is appropriated in the designated area that includes the central part of Cedar City Valley, and this area has been closed to additional development of ground water, except for domestic and stock wells. The 'closed area,' shown by shading on Figure 1, includes the area of intensive pumping for irrigation on the Coal Creek alluvial fan. Sixty-four irrigation wells are located within this closed area.

Within the closed area there are wells ranging in depth from 100 to 600 ft; wells that have flowed by artesian pressure and wells that pump water that is not confined; and wells of contrasting specific capacities (yields per unit of drawdown), contrasts that are explained by the location of the wells with respect to fault barriers. Coal Creek is the principal source of recharge for most of the closed area, but in the northeast corner, near Enoch, there is recharge from other sources. The 14 wells listed in Figure 2 are approximately in order of increasing distance from the apex of the Coal Creek alluvial fan. As a group they are representative of the contrasts in depth, degree of confinement, source of recharge, and effect of fault barriers within the closed area. The general parallelism of the graphs showing water-level fluctuations, based on year-end measurements in these 14 wells, indicates that the effects of recharge, and the effects of discharge (chiefly by irrigation wells), are distributed throughout the closed area, and that therefore all wells may be considered to draw from a common reservoir. The year-to-year changes are greatest in pumped wells close to the source of recharge, such as well (C-35-11)33 aac-1, and least in wells near the margin of the pumping district and on the lower part of the alluvial fan. Thus, well (C-35-12) 34dcd-1, showing little fluctuation, is in the SE 1/4 SW 1/4 SE 1/4 sec 34, T 35 S, R 12 W, near Iron Springs Gap.

In most of these wells the water levels rose markedly in 1937, 1938, 1941, 1942, 1949, and 1952. In each of these years the runoff of Coal Creek was greater than the 20-year (1935-54) average. In general the graphs show the effect of drought in the 1930's, a rise to a maximum in 1942, and a progressive decline in the succeeding 12 years, except in 1949 and 1952.

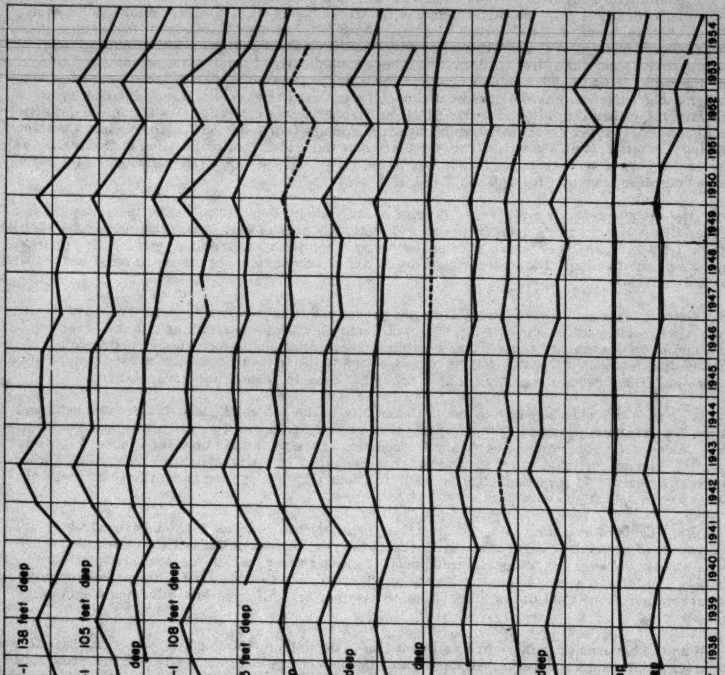

Fig. 2--Annual water-level trends in 14 wells in Cedar City Valley, Utah

Role of ground water in the water economy--In 1930, about 5600 ac ft of water was pumped from 24 wells within the area now designated the closed area of Cedar City Valley. In 1938, pumpage within this area had increased to 9100 ac ft from 54 wells. As shown by Figure 3, the annual pumpage rose to 12,400 ac ft in 1940 and to 17,800 ac ft in 1951. However, in 1945, 1947, 1949, and 1952, years when the runoff of Coal Creek was relatively large, the pumpage for irrigation was very little more than in 1940. The pumpage from wells has been greatest in years when surface-water supplies were least.

The surface-water supplies for Cedar City Valley in most years are greater than the quantities pumped from wells, as shown in Figure 3. Thus diversions from Coal Creek furnish most of the water used for irrigation in Cedar City Valley in an average year. But the quantity of surface water available varies greatly from month to month in each irrigation season (for example, from 21,000 ac ft in May to 900 ac ft in September 1941) and also from year to year (from 450 ac ft in September, 1936 to 1200 ac ft in September 1937). In the Coal Creek basin there are no reservoirs to store water from year to year, or even from May to August, and no suitable sites for development of surface storage. Many holders of surface-water rights therefore pump from wells to supplement their surface supplies in the latter part of the irrigation season and also in years when runoff is less than average.

In wet years, most of the pumping is on ranches where wells constitute the only source of water for irrigation, and in such years the total pumpage in the closed area may be 13,000 ac ft or less. In dry years, however, the draft may be considerably greater than this quantity, to overcome the deficiencies in streamflow and in valley precipitation. In 1951 more than 70 per cent of the water used for irrigation was pumped from wells, but in 1952, with far greater streamflow, only about 20 pct was pumped from wells.

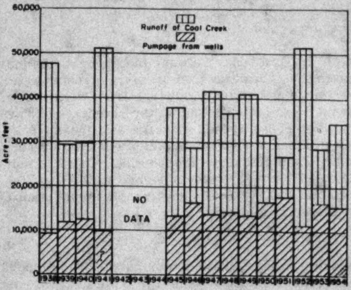

Fig. 3--Total water available for irrigation on the Coal Creek alluvial fan, 1938-40 and 1945-54

Precipitation, runoff, and ground-water storage--In the 48-year period 1907-54, the average water-year precipitation at Cedar City has been 12.33 inches. However, in the latter half of that period (1931-54), the precipitation exceeded this average only in 1932, 1937, 1941, 1942, and 1947. In the last five years (1950-54) the average water-year precipitation has been only 8.50 inches, 61 pct of the long-term average, and this is by far the driest five-year period in the half century of record. By contrast, during the wettest five-year period (1921-25) the precipitation averaged 15.73 inches a year.

The trends in precipitation at Cedar City are shown by the uppermost graph of Figure 4: relatively wet years prior to 1925, dry years and drought until 1938, moderately wet years until 1942, and drought beginning in 1945. Beginning in 1945 precipitation has been below normal every year except 1947. This period has been one of severe drought throughout the southwestern United States. Studies summarized by the U. S. DEPARTMENT OF THE INTERIOR [1951] indicate that this drought is one of the eight greatest droughts that have occurred in the past 600 years. Cedar City is clearly within the area affected by this drought, and has thus been subjected to two intense droughts in the past 20 years.

In the 21 years 1934-54, the runoff of Coal Creek at Cedar City has averaged about 24,000 ac ft. There is evidence that this average is less than the long-term average, just as precipitation in those years was appreciably less than the long-term average. Incomplete records indicate that the runoff of Coal Creek averaged about 40,000 ac ft annually between 1916 and 1926, the maximum being about 74,000 ac ft in 1923. The runoff of 23,000 ac ft in 1919 was the least recorded in any of these early years, but was almost as great as the average for the period 1934-54. The graph on Figure 4 indicates a downward trend in runoff since about 1926, reflecting the trend in precipitation.

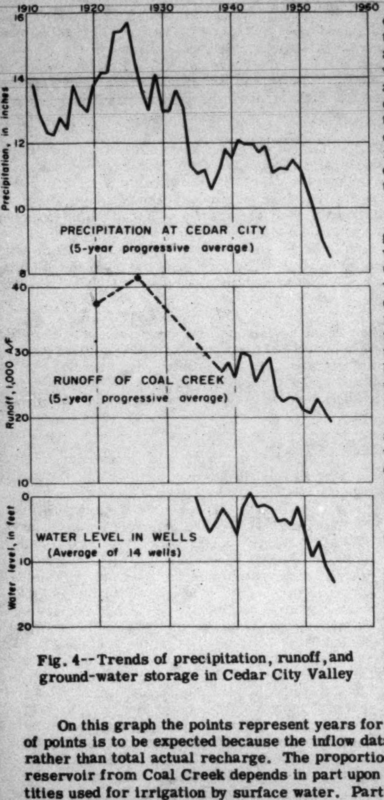

Fig. 4--Trends of precipitation, runoff, and ground-water storage in Cedar City Valley

The third graph on Figure 4 shows the average changes in water levels in the 14 wells whose fluctuations are shown in Figure 2. This graph, indicative of trends in storage in the ground-water reservoir, reflects the general trends in precipitation and runoff. The changes in ground-water storage correlate more closely with trends in runoff than they do with precipitation, notably in 1952 when precipitation at Cedar City was only 10.17 inches, yet runoff of Coal Creek exceeded 40,000 ac ft, because of greater-than-normal accumulation of snow in the tributary drainage basin.

Recharge-discharge relation to changes in ground-water storage--The ground-water reservoir in the closed area probably is recharged by Coal Creek and other smaller streams, by ground-water inflow from the bordering ranges, and by direct precipitation upon the area. Detailed studies indicate that the chief source is Coal Creek, the recharge occurring either by seepage from the stream channel or from diversion ditches, or by percolation from fields irrigated by the stream water. The runoff of Coal Creek may thus be a measure of the quantity available for ground-water recharge. The pumpage from irrigation wells is an essentially accurate measure of the ground-water discharge for beneficial use, because the domestic, stock, and industrial uses are very small in comparison.

The difference between these quantities indicates the spread between potential ground-water recharge and actual discharge from wells. The annual change in ground-water storage, as shown by water-level trends in wells, is a measure of the difference between actual ground-water recharge and discharge from wells. There is some correlation between these annual water-level changes and the Coal Creek runoff minus pumpage, as shown graphically in Figure 5.

On this graph the points represent years for which pumpage has been computed. The dispersion of points is to be expected because the inflow data pertain to potential recharge from Coal Creek rather than total actual recharge. The proportion of water that actually reaches the ground-water reservoir from Coal Creek depends in part upon the rate of streamflow and upon the areas and quantities used for irrigation by surface water. Particularly in periods of high discharge some water may continue down the channel beyond the recharge area; in periods of low flow the natural channels or ditches may be silted enough to inhibit recharge.

The straight line indicates a relationship that will doubtless be refined considerably as data become available for a greater number of years. Current data suggest that the annual flow of Coal Creek must total 12,000 ac ft in order to prevent depletion of ground-water storage, allowing no pumping from wells. Thus in 1951, when the runoff was less than this quantity, the water levels in wells would have declined even if pumping had been prohibited. This 12,000-ac ft flow is a minimum requirement for maintaining equilibrium conditions in the reservoir with no beneficial use. It represents the consumptive use of water by crops irrigated from the streams; the evaporation from ditches, transpiration by bordering willows or native vegetation, and other water that does not reach the ground-water reservoir; and the recharge necessary to balance the natural discharge and movement of ground water from the closed area.

If there is pumping from wells, the irrigation-season flow of Coal Creek must be increased by an amount equivalent to that pumpage in order to hold ground-water storage at equilibrium. Thus in the growing season of 1951, when more than 15,000 ac ft was pumped, the flow of Coal Creek would have needed to be more than 27,000 ac ft to balance this rate of withdrawal. Again, this is a tentative relationship based on meager data.

The slope of the line indicates that the average water levels in wells will rise 1 foot if the potential recharge is about 4500 ac ft greater than the seasonal pumpage, and will drop at the same rate when the seasonal pumpage exceeds the irrigation-season flow of Coal Creek by that amount. If this straight-line relation holds throughout all ranges, the recharge during a very wet year such as 1922 would be enough to raise the average water levels in the closed area by more than ten feet.

Reference to Figure 3 indicates that the closed area obtained less than 30,000 ac ft of water from both surface and ground sources in 1939, 1940, 1946, 1951, 1953, and probably 1943. From present data it would appear that the water resources are adequate for sustained and perennial irrigation of the area that produced crops in those years.

In several other years, of which 1945, 1947, 1948, 1949, and 1954 are typical, the total water available to the closed area was of the order of 35,000 to 45,000 ac ft. It is not known at this time whether the water resources are adequate to sustain an economy requiring this quantity every year, because the available records cover only a period when precipitation was less than the long-term average, and part of which was an outstanding drought.

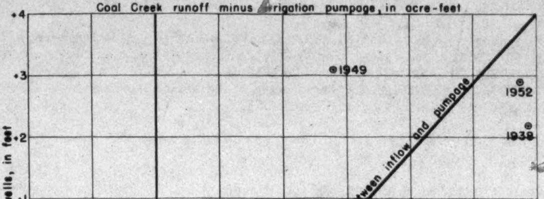

Fig. 5--Recharge-discharge relation to annual changes of water levels in wells in the 'closed area' in Cedar City Valley

In three years (1938, 1941, and 1952) the total available supplies probably exceeded 45,000 ac ft, of which some doubtless had a low order of use during the period of peak stream discharge. Surface-water rights permit a greater total acreage to be irrigated during those years, at least during the period of flood runoff. The record suggests that this irrigation of additional acreage during wet years is beneficial, or at least not detrimental, to the water resources. As shown in Figure 2, the water level in wells rose appreciably in each of those years, and it is likely that irrigation by flood water served, as does water spreading, to augment the natural recharge.

Perhaps the greatest danger of overdevelopment lies in the urge to 'cover in' these intermittently irrigated areas, and give them a perennial water supply by drilling more wells. And the time of greatest danger is not during a series of dry years, but during a wet period when the depleted ground-water reservoir is being replenished. At such times the rise of water levels is likely to be taken as evidence that there is 'unappropriated water,' and inevitably the State Engineer will be urged to relax his rigid restrictions on new development.

As shown in Figure 4, the water levels in the 14 wells in the closed area at the end of 1954 averaged seven feet lower than the minimum reached during the drought of the 1930's, and 14 ft lower than in 1942. If each foot change in water levels represents 4500 ac ft of storage, as suggested by Figure 5, the ground-water storage in the closed area is currently about 30,000 ac ft less than in 1936, and 60,000 ac ft less than in 1942.

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EVAPORATION AND EVAPOTRANSPIRATION INVESTIGATIONS IN THE SAN FRANCISCO BAY AREA

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Abstract--During 1953 and 1954 studies were made to determine probable evaporation and evapotranspiration losses that would occur if barriers were constructed across the San Francisco Bay to exclude salt water. This would create fresh-water pools to conserve water for irrigation, domestic, and industrial use. Available measurements of evaporation and consumptive use of water by vegetation were compiled and analyzed. New climatological stations were established in areas not covered by existing stations and measurements made on evaporation, temperature, humidity, wind movement and precipitation. Evaporation and consumptive use data were correlated with climatological records and estimates were made of annual and monthly rates of evaporation from lake surfaces and consumptive use by marsh vegetation for the 1921-1952 period and for the five critical years, 1923, 1924, 1930, 1931, and 1951.

Introduction

This paper presents the results of a study of evaporation from water surfaces and evapotranspiration (consumptive use) by marsh vegetation in the San Francisco Bay and adjacent areas made by the Soil Conservation Service and the Agricultural Research Service of the United States Department of Agriculture in cooperation with the Division of Water Resources, California Department of Public Works. This study was a contribution to an investigation being made by the State Engineer, involving the whole subject of the feasibility of the proposed barriers across the San Francisco Bay to create fresh-water pools (or lakes). The primary function of such barriers would be the development of a dependable supply of water for irrigation, domestic, and industrial use in the Bay Area and elsewhere.

The time of occurrence and amounts of water losses from fresh-water barrier pools resulting from natural demands of evaporation and evapotranspiration by phreatophytes and hydrophytes growing in and adjacent to the barrier pools are important factors that must be considered in a water-balance inventory of the proposed project.

The authors were assigned the task of determining in about one year the probable average annual and monthly rates of water consumption in the San Francisco Bay area below the confluence of the Sacramento and San Joaquin rivers and the adjacent marsh lands during the period 1921 to 1952, and for critical water years 1923, 1924, 1930, 1931, and 1951. Monthly and annual consumptive-use rates for tules, cattails, and saltgrass were required for these years and use by saltgrass for various depths to the water table in marsh lands. The area covered by this study includes the South San Francisco Bay, San Pablo Bay, Carquinez Strait, Suisun Bay, and delta lands and consists of some 239,000 acres of water surface and 14,400 acres of marsh land (see Fig. 1). The procedure employed to determine the rates of evaporation and evapotranspiration are described and the results are given in this paper.

Evaporation and climatological data

A survey of existing data revealed that evaporation measurements were being made from United States Weather Bureau type pans (four feet in diameter and ten inches deep) at fifteen locations in the San Francisco Bay and Sacramento-San Joaquin Delta area, some of which are shown in Figure 1. A concentration of these records was found along the southern shores of South San Francisco Bay, two records on the northern shore of San Pablo Bay, two on the south edge of Suisun Bay and others in outlying areas at the upper fringe of the delta. Slightly inland, two evaporation records were found near Berkeley and San Leandro.

In order to obtain better coverage of the water-surface areas from which evaporation will take place under a barrier system, it was believed necessary to install three additional evaporation

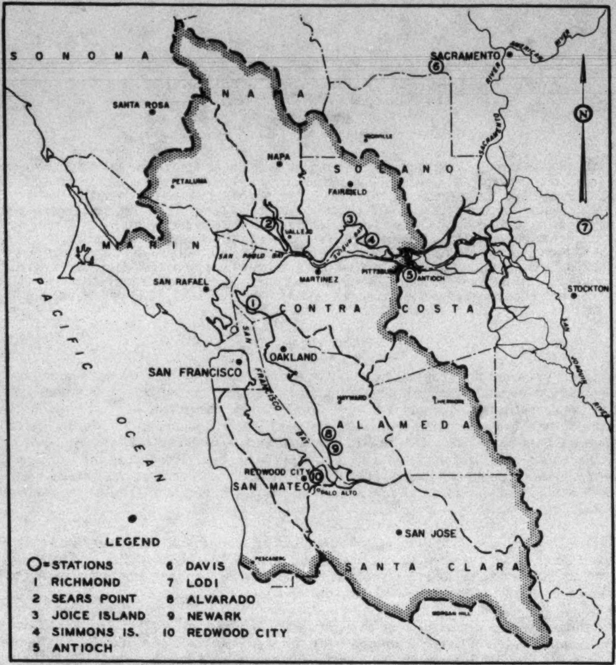
SONOMA
NAPA
SOLANO
MARIN
CONTRA COSTA
ALAMEDA
SAN MATEO
SANTA CLARA
PACIFIC OCEAN
SACRAMENTO
SANTA ROSA
NAPA
PETALUMA
FAIRFIELD
VALLEJO
SAN PABLO BAY
MARTINEZ
PITTSBURG
ANTIOCH
SAN RAFAEL
STOCKTON
OAKLAND
SAN FRANCISCO
SAN FRANCISCO BAY
HAYWARD
REDWOOD CITY
PALO ALTO
SAN JOSE
N
LEGEND
○ = STATIONS
1 RICHMOND
2 SEARS POINT
3 JOICE ISLAND
4 SIMMONS IS.
5 ANTIOCH
6 DAVIS
7 LODI
8 ALVARADO
9 NEWARK
10 REDWOOD CITY

Fig. 1--Map showing location of evaporation and evapotranspiration stations in the San Francisco Bay area

stations at selected locations. Station 1 was installed at the University of California, Richmond Field Station in the City of Richmond. The station is well exposed to the prevailing winds off the bay and believed to represent conditions along the waterfront on the eastern side of San Pablo Bay. Equipment includes an anemometer, raingage, a Weather Bureau type pan and a Young (screened) type evaporation pan (two feet in diameter by three feet deep, set in the ground 2.75 ft, screened with galvanized hardware cloth with 1/4-inch mesh). Temperature, humidity, precipitation and meteorological data are collected by the University of California at the field station immediately adjacent to the evaporation station and the records precede those of the evaporation records by about a year.

Station 2 was installed on the northern edge of San Pablo Bay about one mile north of Sears Point Road and midway between Napa River and Sonoma Creek on the southern levee of South Slough. This station was equipped with a Weather Bureau-type evaporation pan, raingage, thermograph and maximum and minimum thermometers. It represents the conditions along the northerly edge of San Pablo Bay.

Station 3 was installed on Joice Island near Volanti Slough. Equipment consisted of a Weather Bureau-type evaporation pan, anemometer, thermograph, maximum and minimum thermometers, and a raingage. In addition, a tank six feet in diameter and four feet deep was set in an area of tules growing naturally in the shallow water of the island. Tules were transplanted to the tank and the consumptive use determined by measuring the water added to the tank periodically. Ratios were determined at this station between temperature, evaporation from a Weather Bureau-type pan and tules growing in natural environment. Such ratios are available at other localities [BLANEY and Others, 1933; MUCKEL and BLANEY, 1945] and it was deemed advisable to determine if the same ratios held for bay area conditions.

In Table 1 the mean monthly evaporation from Weather Bureau-type pans at the three new stations and some of the other stations in the San Francisco Bay and adjacent areas are shown together with the length of record.

Table 1--Mean monthly measured evaporation from U. S. Weather Bureau-type pans at typical stations in the San Francisco Bay and adjacent areas

Month	San Francisco Bay			San Pablo Bay		Suisun Bay		Delta	
	Alvarado-Neward[a] (30 yr)	Richmond[b] (1 yr)	Upper San Leandro[c] (3 yr)	Sears Point[b] (1 yr)	San Pablo Res.[c] (3 yr)	Antioch[d] (4 yr)	Joice Island[b] (1 yr)	Davis[e] (28 yr)	Lodi[f] (23 yr)
	inch	inch	inch	inch	inch	inch	inch	inch	inch
Jan.	1.48	1.35	1.12	1.37	1.06	1.51	1.38	1.21	1.06
Feb.	2.02	1.72	2.43	2.01	2.32	2.11	1.95	1.96	1.78
Mar.	3.66	2.49	3.49	2.86	3.57	4.32	3.15	3.73	3.54
Apr.	5.00	4.42	4.72	5.05	4.57	6.61	5.45	5.74	5.81
May	6.92	6.52	6.49	7.80	6.56	9.62	8.26	8.31	8.73
June	7.72	7.56	6.72	9.63	7.32	10.98	9.54	9.84	10.44
July	8.23	7.08	8.05	11.82	8.42	12.40	11.44	11.04	11.64
Aug.	7.15	6.25	6.33	6.67	7.06	10.52	7.85	9.86	9.98
Sept.	5.79	5.47	5.59	5.32	5.76	8.25	7.29	7.88	7.55
Oct.	3.94	3.47	3.98	4.62	4.14	5.51	4.24	5.09	4.41
Nov.	2.14	1.32	2.07	1.21	1.99	2.20	1.25	2.44	1.93
Dec.	1.41	2.10	1.29	1.35	1.34	1.46	1.33	1.22	1.00
Annual	55.37	49.75	52.28	59.71	54.11	75.49	63.13	68.12	67.92

[a] Leslie Salt Co. (U. S. Weather Bureau) (Stations 8 and 9, Fig. 1).

[b] Stations established for this study (Stations 1, 2, and 3, Fig. 1).

[c] East Bay Municipal Utility District.

[d] U. S. Bureau of Reclamation (not on waterfront) (Station 5, Fig. 1).

[e] University of California and U. S. Weather Bureau (Station 6, Fig. 1).

[f] U. S. Weather Bureau (Station 7, Fig. 1).

Temperatures were found to be recorded at 22 locations in the immediate vicinity of the bay area. Of these, seven locations had records extending over the period 1921 to 1952 inclusive. Wind movement is also being recorded at several stations as well as humidity at the major Weather Bureau and Airport stations.

Water consumption formula

The processes of evaporation from a free water surface and plant transpiration are similar in that each is influenced by climatic conditions. The quantity of water transpired by plants depends upon the amount of water at their disposal as well as on temperature and dryness of the air, intensity of sunlight, wind movement, length of growing season, stage of plant development, amount of foliage, and the nature of its leaf.

Because measurements of evaporation and evapotranspiration are meager in the San Francisco Bay region and in order to fulfill the requests of the State Engineer for monthly and annual rates of water consumption for the years 1923, 1924, 1930, 1931, and 1951 and 1921-1952 period, it was necessary to extrapolate existing data in the Bay area and elsewhere by the method developed by BLANEY and MORIN [1942], BLANEY and CRIDDLE [1950]. Briefly, the procedure is to correlate existing monthly evaporation and consumptive-use data with monthly temperature and per cent of daytime hours. The coefficients so developed are used to transfer evaporation and consumptive use data from one section to other areas where only climatological data are available.

Neglecting the unmeasured factors, evaporation and evapotranspiration vary with the temperature and the daytime hours, and available moisture. By multiplying the mean monthly temperature t by the monthly per cent of daytime hours of the year p, there is obtained a monthly water use factor f. Then it is assumed that the water use varies directly as this factor when an ample water supply is available. Expressed mathematically, $U = KF$ = sum of kf where

U = use of water (evaporation or consumptive use) in inches for any period
F = sum of the monthly water use factors f for the period (sum of the products of mean monthly temperature and monthly per cent of annual daytime hours; $t \times p/100$)
K = empirical coefficient (annual or period)
t = mean monthly temperature, °F
p = monthly per cent of daytime hours of the year
$f = t \times p/100$ = monthly water use factor
k = monthly empirical coefficient
$u = kf$ = monthly use of water (evaporation or consumptive use) in inches

By knowing the monthly evaporation or consumptive use in some locality an estimate of the water use in some other area having similar climatic conditions may be made by application of the formulas $U = KF$ or $u = kf$.

Determination of water consumption rates

The water use formula $U = KF$ has been employed in computing rates of evaporation and evapotranspiration in many areas in California [BLANEY and EWING, 1946] and other parts of the United States [BLANEY and CRIDDLE, 1949] and the World.

Temperature records--Because many of the records of temperature in the San Francisco Bay and adjacent areas do not cover the entire period of the study, 1921-1952, it was necessary to extend available monthly temperature data to cover missing years and mean for the period 1921-1952.

Five temperature records which covered the entire period being investigated were found for the area immediately adjacent to the bays. These were at San Francisco, San Jose, Oakland, Antioch, and Crockett. These long-time records were used as bases to extend data at locations of short record. The temperature data at all stations were processed to determine at which station the temperatures deviated from normal in a like proportion. When this was completed the proper base station was found for each of the stations of short record and the missing records calculated.

Coefficients (k)--After having the mean monthly temperatures t for the various locations for which water consumption was desired, the next step was to determine the monthly coefficients k to apply to the formula $u = kf$ based on actual measurements in areas having similar climate to the San Francisco Bay region. Fortunately, there exists long-term measurements of evaporation from Weather Bureau-type pans in the Bay and adjacent areas [YOUNG, 1947]. Some short-period measurements of evapotranspiration of marsh vegetation are available in the Bay and other areas in California [BLANEY and Others, 1933; MUCKEL and BLANEY, 1947].

The monthly evaporation coefficients k employed in computing evaporation by the formula $u = kf$ are based on monthly Weather Bureau pan evaporation and temperature measurements at Newark-Alvarado for 'coastal' conditions and on average of monthly evaporation and temperature records at Newark-Alvarado, Lodi, and Davis for 'inland' conditions. Table 2 illustrates the method employed to compute these monthly coefficients. In the case of evaporation from lake surfaces it was necessary to apply a reduction factor to the pan evaporation. The reduction factor as found by earlier work in Southern California was checked in the Bay area, in one case by the comparison of evaporation from a Weather Bureau-type pan with that of a screened-type pan at the Richmond Station. The screened-type pan has a reduction coefficient of about 1. Comparisons were also made at two large reservoirs of the East Bay Municipal Utility District where Weather Bureau type pans are operated along with floating pans. The monthly pan factors for reducing Weather Bureau type pan evaporation to lake evaporation are shown in Table 3. The computed average monthly lake evaporation for various points in the San Francisco Bay are given in Table 4 for the period 1921-1952.

For the tule and saltgrass water use, no reduction factors were necessary as the results were based on tanks set in a natural environment. The results obtained by the formula, $u = kf$, were checked for evaporation and tule use by actual measurements in the Bay area. A tank containing tules was installed in a swamp area of Joice Island as a part of this investigation. As stated before, Table 2--Mean monthly temperature, evaporation from Weather Bureau pan, and calculated monthly consumptive-use factors and coefficients, Alvarado-Newark, California, South San Francisco Bay, for period 1924-1952

Month	Mean temperature t	Daytime hours p	Consumptive use factor f	Evaporation u^a	Consumptive use coefficient	
					k^b	k^c
	F	pct		inch		
January	47.9	6.90	3.30	1.48	0.45	0.45
February	51.1	6.81	3.48	2.09	0.60	0.60
March	54.1	8.34	4.51	3.69	0.82	0.80
April	56.7	8.88	5.03	4.99	0.99	1.00
May	59.7	9.90	5.91	6.90	1.17	1.15
June	62.6	9.92	6.21	7.68	1.24	1.25
July	64.3	10.07	6.48	8.10	1.25	1.25
August	63.9	9.46	6.04	7.12	1.18	1.20
September	64.1	8.38	5.37	5.78	1.08	1.10
October	60.5	7.81	4.72	3.92	0.83	0.85
November	54.3	6.84	3.71	2.14	0.58	0.60
December	49.8	6.69	3.33	1.40	0.42	0.40

[a] Measured evaporation from Weather Bureau pan.

[b] $k = u/f$ = evaporation/consumptive-use factor.

[c] k rounded to nearest five hundredths for computing evaporation for coastal temperature stations.

Table 3--Monthly reduction pan coefficient for a Weather Bureau-type pan, San Francisco Bay area, California[a]

Month	Coefficient	Month	Coefficient	Month	Coefficient
January	0.60	May	0.75	September	0.75
February	0.70	June	0.80	October	0.75
March	0.70	July	0.80	November	0.70
April	0.75	August	0.80	December	0.65
				Annual	0.75

[a] Based on evaporation studies in Southern California.

Table 4--Computed monthly lake evaporation in San Francisco Bay and adjacent areas, California. 1921-1952 period average

Month	Newark	Oakland Airport	Hamilton Field	Crockett	Antioch	Richmond	Sears Point Road	Joice Island
	inch	inch	inch	inch	inch	inch	inch	inch
January	0.82	0.81	0.79	0.81	0.78	0.79	0.80	0.80
February	1.39	1.38	1.37	1.41	1.37	1.19	1.00	1.41
March	2.47	2.45	2.44	2.53	2.51	1.78	2.04	2.42
April	3.76	3.71	3.78	3.84	4.23	3.59	4.44	3.96
May	5.00	4.94	5.10	5.12	6.47	4.99	5.98	6.14
June	6.20	6.10	6.43	6.45	7.77	6.24	7.86	7.72
July	6.46	6.34	6.75	6.74	8.58	6.38	9.57	8.99
August	5.74	5.63	5.94	6.00	7.55	5.13	5.38	6.80
September	4.30	4.26	4.40	4.45	5.60	4.10	3.99	5.41
October	3.30	3.28	3.32	3.42	3.45	2.60	3.46	3.24
November	1.49	1.48	1.46	1.52	1.46	0.94	0.87	0.88
December	0.83	0.82	0.80	0.81	0.78	1.29	0.83	0.86
Annual	41.76	41.20	42.58	43.10	50.55	39.02	46.22	48.63

however, the actual measurements did not extend over the period required or at enough locations and the indirect method had to be employed. The short-time checks made, however, indicate that the estimates are sound. Table 5 shows the monthly consumptive use coefficients k for tules-cattails and saltgrass at various depths to water table. The computed average monthly evapotranspiration by tules is shown in Table 6 and for saltgrass in Table 7.

Table 5--Monthly consumptive use coefficients k for marsh vegetation (tules, cattails and saltgrass for various depths to water table) San Francisco Bay and adjacent areas, California

Month	Tules[a]		Saltgrass[b]							
	Coastal	Inland	Coastal				Inland			
			Depth to water table				Depth to water table			
			1 ft	2 ft	3 ft	5 ft	1 ft	2 ft	3 ft	5 ft
January	0.45	0.50	0.40	0.60	0.55	0.45	0.45	0.65	0.60	0.50
February	0.50	0.65	0.45	0.60	0.55	0.55	0.50	0.65	0.60	0.60
March	0.65	0.90	0.50	0.65	0.60	0.55	0.55	0.70	0.65	0.60
April	0.90	1.15	0.65	0.65	0.60	0.50	0.70	0.70	0.65	0.55
May	1.15	1.30	0.70	0.65	0.40	0.35	0.75	0.70	0.45	0.40
June	1.15	1.35	0.90	0.65	0.35	0.30	1.00	0.70	0.40	0.35
July	1.25	1.40	1.00	0.65	0.35	0.30	1.10	0.70	0.40	0.35
August	1.15	1.35	0.95	0.65	0.35	0.30	1.00	0.70	0.40	0.35
September	1.15	1.30	0.75	0.65	0.35	0.30	0.80	0.70	0.40	0.35
October	1.00	1.20	0.65	0.65	0.40	0.40	0.70	0.70	0.45	0.45
November	0.80	0.90	0.60	0.65	0.55	0.55	0.65	0.70	0.60	0.60
December	0.50	0.50	0.40	0.50	0.50	0.50	0.45	0.55	0.55	0.55

[a] Coastal values based upon tank studies in San Luis Rey Valley [MUCKEL and BLANEY, 1945]; inland values based upon tank studies in San Luis Rey Valley averaged with unpublished tank studies on Simmons Island, 1932 (Station 4, Fig. 1).

[b] Based upon 1931-32 tank studies at Santa Ana, California, [BLANEY and Others, 1933]; increased by ten per cent for inland areas.

Table 6--Computed average monthly evapotranspiration by marsh vegetation (tules-cattails) for San Francisco Bay and adjacent areas, California, 1921-1952[a]

Month	Newark	Oakland Airport	Hamilton Field	Crockett	Antioch	Joice Island	Sears Point
	inch	inch	inch	inch	inch	inch	inch
January	1.5	1.5	1.4	1.5	1.5	1.5	1.4
February	1.7	1.7	1.7	1.8	2.2	2.2	1.7
March	2.9	2.9	2.9	3.0	4.1	4.2	2.8
April	4.5	4.5	4.5	4.6	6.1	6.1	4.2
May	6.8	6.7	6.9	6.9	8.4	7.9	6.7
June	7.1	7.0	7.4	7.4	9.5	9.1	7.2
July	8.1	7.9	8.5	8.4	10.4	10.0	8.1
August	6.9	6.8	7.2	7.3	9.3	9.2	6.9
September	6.2	6.1	6.3	6.4	7.7	7.4	5.9
October	4.7	4.7	4.7	4.9	5.9	5.7	4.5
November	3.0	3.0	2.9	3.0	3.3	3.2	2.8
December	1.7	1.6	1.6	1.6	1.6	1.5	1.5
Mean Annual	55.1	54.4	56.0	56.8	70.0	68.0	53.7

[a] These rates apply to large areas of marsh vegetation.

Application of rates of use to large areas

The results of determinations of rates of water consumption, shown in Tables 4, 6, and 7, when reduced from inches to acre feet per acre, may be used to estimate gross free water losses in acre feet from the pools and land areas effected by proposed barriers to exclude salt water. Table 8 summarizes the rates of use in acre feet per acre. After the area of water surface of a lake or pool and the fringe area of marsh vegetation above a proposed barrier site have been determined, Table 7--Computed average monthly evapotranspiration by saltgrass (with water table at two feet) for San Francisco Bay and adjacent areas, California, 1921-1952

Month	Newark	Hamilton Field	Crockett	Antioch
	inch	inch	inch	inch
January	2.0	1.9	1.9	2.0
February	2.1	2.0	2.1	2.2
March	2.9	2.9	3.0	3.2
April	3.3	3.3	3.3	3.7
May	3.8	3.9	3.9	4.5
June	4.0	4.2	4.2	4.9
July	4.2	4.4	4.4	5.2
August	3.9	4.0	4.1	4.8
September	3.5	3.6	3.6	4.1
October	3.0	3.1	3.2	3.5
November	2.4	2.4	2.5	2.6
December	1.7	1.6	1.6	1.7
Mean annual	36.8	37.3	37.8	42.4

Table 8--Computed mean annual evaporation from fresh-water lakes and evapotranspiration by marsh vegetation, 1921-1952, at various locations in the San Francisco Bay area

Location	Water consumption, acre feet per acre				
	Lake evaporation	Evapotranspiration			
		Tules	Saltgrass[a]		
Newark	3.48	4.59	3.07	2.15	1.94
Oakland Airport	3.43	4.53	...	...	...
Sears Point Road	3.85	4.48	...	...	...
Hamilton Field	3.55	4.67	3.11	2.16	1.94
Crockett	3.59	4.73	3.16	2.20	1.98
Antioch	4.21	5.84	3.54	2.52	2.29
Joice Island	4.05	5.67	...	...	...

[a] Columns 4, 5, and 6 are respectively for depth of two, three, and five feet to the water table.

Table 9--Estimates of evaporation and evapotranspiration losses from a fresh-water pool with a barrier at Point San Pablo

Month	Evaporation (113,600 acres)	Evapotranspiration (18,780 acres)	Total (132,380 acres)
	ac ft	ac ft	ac ft
October	27,700	7,930	35,630
November	11,600	4,730	16,330
December	7,700	2,400	10,100
January	7,800	2,350	10,150
February	12,900	3,080	15,980
March	24,600	5,330	29,930
April	40,400	8,110	48,510
May	55,300	12,210	67,510
June	67,100	12,660	79,760
July	77,200	14,890	92,090
August	56,700	12,580	69,280
September	43,100	10,460	53,560
Total	432,100	96,730	528,830

these unit rates, when multiplied by acreage involved, give the gross evaporation and evapotranspiration losses in acre feet. Table 9 shows preliminary estimates of water losses by evaporation and evapotranspiration which might have occurred if a barrier to exclude salt water had been constructed across San Francisco Bay at Point San Pablo.

In an accounting of the water supply in the operation of a barrier pool, evaporation losses must be considered, as sometimes they are of such moment that the feasibility of a project may hinge on this one item. For example, in the case of a barrier at Point San Pablo, Table 9 indicates that the combined evaporation and evapotranspiration losses amount to 92,000 acre feet for the month of July. This is equivalent to a continuous flow of about 1500 cfs.

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THE DISPLACEMENT OF CALIBRATION CURVES FOR ELECTRICAL SOIL-MOISTURE UNITS

Irwin Remson and G. S. Fox

Abstract--Electrical-resistance blocks were calibrated for use in soil-moisture studies at Seabrook, N. J. Curves from successive laboratory calibrations are positioned differently because of the effects of chemical quality of the water used, drying techniques, and other factors. Furthermore, the laboratory curves are displaced from the field calibration curves because of the difficulty of establishing moisture equilibrium in laboratory samples. It is believed that the results demonstrate the general unreliability of laboratory calibrations when compared with field calibrations of soil-moisture blocks.

Introduction--Electrical-resistance blocks are used in making measurements of soil moisture in many hydrologic studies. Despite their deceptive simplicity, the units are difficult to calibrate and may show erratic results in use. Some investigators, after making time-consuming calibrations and studies, have found the performance of such blocks to be unsatisfactory. Because most of the records of the unsuccessful attempts are not published, it is difficult to determine whether they resulted from improper technique, from the nature of the soils involved, or from inherent failings in the method. Therefore, the writers believe that there is a need for appraisal of the performance of the blocks in different studies. This paper will describe one set of experiences, using these instruments, in the hope that it will be of value to investigators in this field.

The U. S. Geological Survey is studying ground-water recharge at Seabrook, N. J. Large volumes of waste water from a cannery are sprayed in a wooded area through large irrigation nozzles [REMSON, 1954, pp. 4-19]. In order to study the movement of water from the land surface to the water table, the installation of nylon, plaster of Paris, and fiber-glass blocks throughout the 17 ft of unsaturated material above the water table was planned. However, difficulties in obtaining satisfactory calibration curves for the approximately 50 units studied resulted in a decision to use the blocks only in the first four feet below the land surface.

Calibration of the resistance units--The soil in the study area is Sassafras loamy sand, and the underlying geologic material is mainly sand and gravel of the Cape May formation of Pleistocene age. In order to obtain soil samples for use in calibrating the blocks, a pit three feet square was dug in this material to the water table. The resistance blocks were pressed edgewise into the face of the pit, and relatively undisturbed cores of soil containing the blocks were obtained and prepared according to the methods recommended by HENDRIX and COLMAN [1951]. The cores containing the fiber-glass units were cut out of the face of the pit in plexiglas tubes by means of a special volume sampler [SMITH and STALLMAN, in press]. The cores containing the larger nylon and plaster of Paris units were taken in lacquered no. 2 cans. Because of the sandy nature of most of the materials, there was relatively little compaction during sampling.

The laboratory calibrations were made according to the directions of COLMAN [1950, p. 1-20]. The soil samples were saturated from the bottom in order to prevent the trapping of air bubbles. They were then dried to different moisture contents and placed in humidors in which the air was maintained at a relative humidity of 98 pct for 24 hours before each measurement. This 'equilibration' technique was intended to bring about moisture equilibrium in the soil sample and the block. Because the soil-moisture blocks were to be used in studying the movement of artificially recharged water, samples of this water, the analyses of which are shown in Table 1, were used for the calibration. Smooth curves were obtained for all the blocks from the first drying period, as shown in Figure 1.

A second calibration of the same blocks was undertaken because of concern over the stability of the curves. With some exceptions, the new calibration curves were similar in shape to those obtained previously, but they were displaced to the left, as shown in Figure 1. A displacement to the left indicates a lower resistance at the same moisture content. For nearly every unit, a third drying period produced a curve that was very similar in shape and position to that derived from the second drying period.

Table 1--Chemical analyses[a] of the recharge water used for calibrating the soil-moisture blocks (parts per million except color, pH, and specific conductance)

Item	Period 1	Period 2	Period 3
Date of collection of water sample (1952)	Mar. 18	June 25	Sep. 19
Color	1	8	2
pH	5.3	6.4	4.9
Hardness as CaCo3	42	47	46
Noncarbonate hardness	40	11	45
Dissolved solids	136	194	232
Specific conductance at 25°C(micromhos)	258	349	460
NO_2	0.0	0.5	0.0
Li	0.0	0.8	0.8
CO_2 (calc)	18	8.8	52
Zn	0.0	0.0	0.1
Al	0.0	0.0	1.0
Cu	0.00	0.00	0.00
Fe, total	0.57	1.3	0.95
Fe in solution at time of analysis	0.04	0.06	0.09
Mn	0.01	0.00	0.09
SiO_2	6.6	8.2	8.8
Ca	10	11	11
Mg	4.1	4.8	4.6
Na	23	40	55
K	6.3	6.4	7.0
CO_3	0	0	0
HCO_3	2	14	2
SO_4	20	17	14
Cl	44	74	106
F	0.4	0.6	0.4
NO_3	16	7.8	14
PO_4	0.3	0.5	0.1

[a] Analyses by D. Singman, U. S. Geological Survey.

In order to test the hypothesis that part of the change in the relative positions of the first- and second-drying-period curves was caused by a difference in the quality of the calibration water, the cores were put through additional drying periods in which distilled water was used to saturate them. The curves for the fiber-glass units for two periods in which distilled water was used were relatively unaffected, as shown by Figure 1a. Most of the curves for the plaster of Paris blocks, for three periods using distilled water, showed slight shifts to the right towards the first-period calibration curves. Most of the curves for the nylon blocks, in three periods using distilled water, showed marked shifts toward the first-period curves, as shown in Figures 1b and 1c. However, there were curves for nylon and plaster of Paris units that showed no shift at all and a very few that showed additional shifts to the left. An extreme case is shown in Figure 1d.

After the last drying period was completed, 18 of the soil samples containing resistance blocks were emplaced in the field at depths of 1/3 foot to four feet. It was not possible to replace them in the sampling pit because of the nature of the studies involved. Therefore, an emplacement pit was dug about ten feet from the original pit. Field examination showed the materials at the two pits to be similar. This is borne out by the particle-size analyses shown in Table 2. Therefore, the cores containing the resistance blocks were placed in holes in the side of the emplacement pit so that the soil surrounding the blocks would remain relatively undisturbed, and the pit was backfilled with the original soil.

In order to allow time for the soil to settle, field calibration of the units was delayed for almost three months after the installation was completed. No irrigation water was applied to the area containing the soil-moisture units before or during the field-calibration period. Periodically, triplicate samples of soil were taken close to the pit at each level at which the units were placed. The mois-

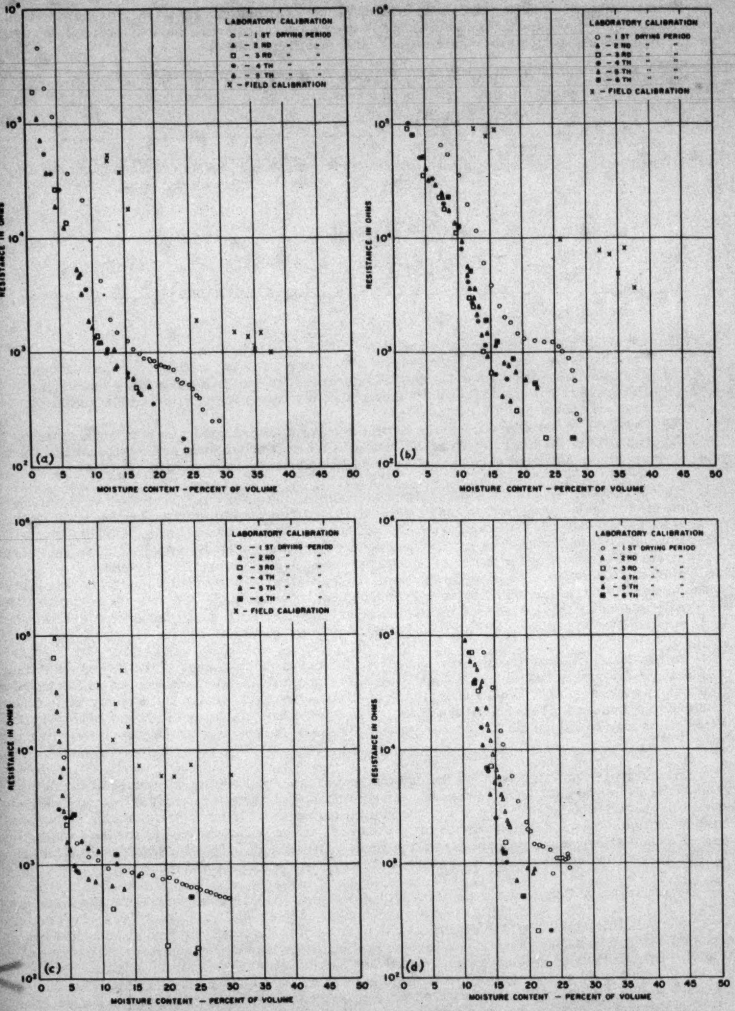

Fig. 1--Calibration curves for resistance blocks, (a) for the fiber-glass block for the 1/3 foot level; (b) for the nylon resistance block for the 1/3-foot level; (c) for the nylon resistance block for the three foot level; (d) for the nylon resistance block for the eight foot level; the open symbols indicate the use of irrigation water, and the solid symbols indicate the use of distilled water ture content of each sample, determined by oven drying, was plotted against the resistance value measured at the time of sampling. As shown in Figures 1abc, the resistance determinations are far to the right of the laboratory-calibration points for all the blocks.

Table 2--Comparison of particle-size distributions of materials at the sampling pit and at the block-emplacement pit; particle-size analyses were made by the hydrometer method

Depth	Sand		Silt		Clay	
	Sampling pit	Emplacement pit	Sampling pit	Emplacement pit	Sampling pit	Emplacement pit
ft	pct[a]	pct[a]	pct[a]	pct[a]	pct[a]	pct[a]
0 - 1	75	77	8	7	17	16
1 - 2	68	72	12	10	20	18
2 - 3	78	82	6	5	16	13
3 - 4	89	89	3	3	8	8

[a] Per cent by weight.

Discussion of results-- Five facts are shown by the calibration data.

(1) The curves for Period 2 are to the left of the curves for Period 1 for most of the blocks.

(2) The curves for Period 3 coincide with the curves for Period 2 for most of the blocks.

(3) The curves for Periods 4, 5, and 6 (using distilled water) for most of the blocks tend to shift back toward the curves for Period 1.

(4) The field calibration curves are far to the right of the laboratory curves for all the blocks.

(5) The shift of the field curves to the right was the only occurrence common to all the blocks tested; there were individual exceptions to each of the generalizations given in (1) to (4) above.

The high conductance of the water used in the calibrations (Table 1) is believed to be partly responsible for the displacement of the curves for Period 2 to the left of those for Period 1. Salts, of course, accumulated in the resistance units and cores as the water evaporated during Period 1. Therefore, the conductance increased as the water of Period 2 redissolved some of the salts, giving a lower resistance reading for the same moisture content during that period. Evidence for this is that, after distilled water was used, some of the curves began to shift back to the right, probably because some of the accumulated salts were leached out. It may be that the salt accumulation during the second drying period was counterbalanced by the leaching of salt during the third wetting so that no shift occurred from Period 2 to Period 3 for most blocks.

During the distilled-water periods, the curves for the nylon units showed the largest shift back to the right, the curves for the plaster of Paris units showed little shift, and the curves for the fiber-glass units showed no shift. In addition, there is a suggestion that greater shifts occurred in soils of higher sand content. That not all the blocks responded in the same way to the saturation in distilled water may be due partly to differences in the sizes of the cores containing the three types of units.

The quality of the water used for the calibration probably was not the only cause of the shifts from Period 1 to Period 2. The curves for some units showed very little recovery to the right, and others did not show any shift after saturation in distilled water. Furthermore, other investigators have found the curves for the second drying period to be to the left of the curves for the first drying period when distilled water was used for all periods [BOUYOUCOS, 1952; HENDRIX and COLMAN, 1951]. Therefore, factors other than water quality affect the positions of the curves.

Bouyoucos found the curve for the first drying period to be unreliable when the nylon block is used. He attributes this to the effect of dyes in the nylon fabric [BOUYOUCOS, 1952]. The writers, however, have found the curve for Period 2 to be to the left of the curve for Period 1 in all three types of units. In addition, Hendrix and Colman have found the same curve displacement when calibrating fiber-glass units in the laboratory after they had been in the field for 14 months. They attribute the shift to disturbing of the soil during the insertion of the block and the removal of the core from the wall of the pit. Although the cores were soaked carefully before each drying period, it is possible that the curves for the first drying period are to the right of the true position because of incomplete saturation of the blocks. In reference to this, Bouyoucos suggests that discrepancies in resistance readings may be due to air bubbles collecting on the electrodes [BOUYOUCOS, 1949].

Field-calibration curves for all the units put back into the soil were to the right of the corresponding laboratory-calibration curves, including those derived using distilled water. Therefore, the differences in the position of the laboratory and field curves cannot be attributed entirely to differences in the chemical quality of the water in the laboratory and in the field.

Other investigators have found relative displacements between laboratory and field curves when using distilled water for their laboratory calibrations. For example, field curves developed by Hendrix and Colman fell to the left of the corresponding laboratory curves when granulated samples were used for the laboratory calibrations. They attribute the effect to departures from natural bulk densities and structures in the granulated samples. They indicate that the use of undisturbed cores for the laboratory calibrations would eliminate this effect. However, BETHLAHMY [1952] and the writers have found differences of position between the laboratory and field curves when using relatively undisturbed cores.

CARLSON [1953] has shown that the air in the chamber in which a relative humidity of 98 pct is maintained dries the surfaces of the cores slightly instead of equilibrating them. He has shown that 'surface evaporation dries natural cores and creates a moisture gradient that remains regardless of the equilibration treatment.' EDLEFSON and ANDERSON [1942, p. 417] have shown 'that even after one month, the plaster of Paris block does not attain equilibrium if surrounded by soil the moisture content of which is in the lower quarter of the range of available moisture to plants.' The work of the writers bears out these observations. For example, a 50-gallon drum containing sand was left to dry in a heated laboratory for six weeks. Although the surface was air dry, the soil at a depth of six inches was still at field capacity at the end of the period, showing the presence of a moisture gradient.

The results of some studies suggest that the capillary conductivity of the drying soil on the outside of the core will become negligible in the drier ranges of soil moisture [MOORE, 1939]. Under such conditions, equilibration can be brought about only by the slow process of vapor transfer. Therefore, the technique of drying cores by surface evaporation may result in higher moisture contents around the resistance units than at the outside of the cores. The laboratory calibrations consequently show lower resistances for the same moisture contents than do field calibrations and lie to the left of the field curves. KELLEY [1944] has shown that when calibrations are performed for units surrounded with only half an inch of soil, fairly uniform moisture contents can be obtained. However, as shown by HENDRIX and COLMAN [1951] relative displacement of the field and laboratory curves will still result because of the unavoidable disturbance of bulk density and structure in the small samples.

Conclusions--Except for the relative displacements of the field and laboratory curves, no uniform pattern of behavior could be found that applied to all the units. For example, Figure 1d shows calibration curves for the finest-grained material in the profile, and the trends shown by these curves are completely different from the other trends. Therefore, there are clearly several different factors that determine the shapes and positions of the laboratory-calibration curves. Some of these are soil texture and structure, chemical content of the calibration water, method of drying, techniques of equilibration, and sampling methods. These conclusions, coupled with the fact that the laboratory curves are displaced from the field curves because of the difficulty of bringing about equilibration, indicate the general unreliability of laboratory calibrations of soil-moisture resistance blocks.

Acknowledgments--The Seabrook Farms Co. generously permitted much of this work to be done on its property and in its laboratories. This work was accomplished with the informal assistance and cooperation of The Laboratory of Climatology of the John Hopkins University. W. O. Smith, physicist of the U. S. Geological Survey, gave much valuable information and advice relative to this work. All phases of the Seabrook investigations have been facilitated by the helpful supervision and cooperation of H. C. Barksdale, staff engineer of the U. S. Geological Survey.

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A SMALL PORTABLE METER FOR SOIL HEAT CONDUCTIVITY AND ITS USE IN THE O'NEILL TEST

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Abstract--A hypodermic needle is fitted, in its bore, with an electrical heating wire and a thermocouple. With certain precautions, its temperature increase yields data of soil heat conductivity. Very large local variations of the heat conductivity λ were found in the upper centimeters of the surface by this instrument at the USAF Great Plains Turbulence Project at O'Neill, Nebraska, in 1953.

Principle--The mathematical analysis in the previous article shows how a heated compact cylinder serves to measure the heat conductivity λ, and a heated hollow cylinder or plate measures the product $\lambda \rho c$ = Conductivity × density × specific heat. It will, therefore, be possible to measure both quantities by remote control on a permanent basis or from point to point. One has simply to insert the two instruments into the soil and measure their temperature increase with time. It seems impossible to measure λ and ρc or any of the combinations $\kappa = \lambda/\rho c$ and $\lambda \rho c$ using data of compact cylinders only. A combination of temperature changes with time of the day and depth might, however, yield κ data, which in turn could be combined with experimental λ data to derive ρc.

B. Morse of this Department, constructed the first permanently installed λ meters in this country. They are compact cylinders of finite length built for permanent installation. Herein is described another form of a finite compact cylinder which is easily inserted into and removed from any kind of sand, soil, mud, gravel, etc. The necessary disturbance of the soil is small. Calibration and fabrication can be easily standardized in this rather inexpensive instrument. As the field test has shown, local variations of λ can be unexpectedly large.

Construction--The needle λ meter, in the form used in the 1953 Great Plains Turbulence Project Test at O'Neill, Nebraska, was constructed by W. W. Bahn of this Department. It consists of a stainless steel hypodermic needle and is 2.5 cm long and 0.07 cm thick. A thin heating wire with a resistance of 4.5 ohms or 1.8 ohm cm^{-1}, is stretched out as a loop in the inner bore. A thermocouple (stainless steel needle and a constantan wire) is soldered in a tiny hole drilled through one wall of the needle, near its center. It thus records the temperature of the needle wall. A thermocouple in the bore of the needle would suffer from too close a contact to the heating wire. The constantan wire and a brass wire soldered to the needle support lead to the reference junction in a thermos bottle and thence to a galvanometer. The 'secondary' thermocouple (stainless steel and brass) is practically ineffective. The resistance of the thermocouple is 6.8 ohms. The remaining free spaces in the needle bore are filled with a plastic.

A short series of laboratory test calibrations were made using a General Electric recording potentiometer with less than 0.2 sec response time. (This test used facilities of the USAF School of Aviation Medicine.) For the field tests a rather slow needle type microammeter had to be used. It was dead beat damped and reached 90 pct of the final value in ten seconds. The scale value was 0.42°C per division. Calibration with water and soil tests were made with the same technique.

Calibration--As shown in the immediately preceding paper, calibration can be done by comparison with a substance of known λ, provided $1<\delta<30$. This excludes the use of fluffy materials for such calibrations. δ is the ratio of volume specific heats of cylinder and soil.

Figure 1 shows examples of calibrations. In the abscissa T and q are observed; the ordinate is $\alpha/\delta = \lambda t/\rho^* c^* a^2$ where t is observed and $\rho^* c^* a^2$ is a known instrument constant. The theoretical curve $\delta = 1$ and the experimental one for water are as close as could be expected. The value of λ was taken from known data. The water contained small amounts of suspended cotton to prevent convection. Using standard data again for λ the observed curve for mercury can be drawn. It initially lies close to the expected one. The later deviation cannot be explained yet.

Pilot experiments were also made with fluffy materials, such as loose cotton. Its ρc was estimated as 0.001 and, consequently, the theoretical curve for $\delta = 1000$ was drawn in Figure 1. Since

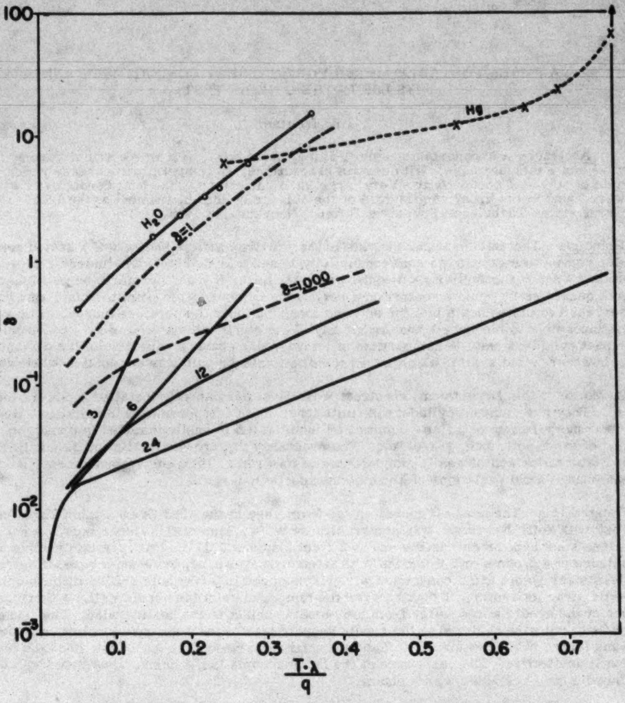

Fig. 1--Calibration of needle λ - meter; T = temperature increase of needle; q = its heating; λ = heat conductivity of soil or test substance; t = time; $\rho^* c^*$ volume specific heat of needle; a its radius; Curves δ = 1 and δ = 1000 are theoretical; curves observed in H_2O and Hg are drawn using λ = 1.4×10^{-3} and λ = 0.02 respectively; curves 3, 6, 12, 24 are drawings of observations with loose cotton using different tentative λ - values

the actual λ was not known, curves were drawn for tentative values of λ = 3, 6, 12 and 24 × 10^{-5} cgs. Obviously, longer exposures and some better knowledge of ρc would be necessary so as to derive a proper λ value.

The end of the usable data in a continuous record is given by the rather sudden deviation of the curve from the logarithmic increase. This deviation is caused by the finite length of the cylinder (see Fig. 1 of the previous paper). In the actual field tests there was generally a usable time between ten and 40 sec after heating started. This concerns the straight part of the (T, t) curve on log paper. Figures 1 and 2 of the previous paper explain the deviations from the straight line.

Consequently (5b) of the previous paper was used inthe field tests. The constant C_1 was taken from measurements in water; this value is valid for $1<\delta<30$, and is higher by 40 per cent for δ = 100. Without proper knowledge of ρc of the soil only guesses as to the influence of ρc variations can be made. Appreciable errors would, however, be restricted to the smallest apparent λ values. The error in our series hardly exceeds 20 per cent.

Field Tests in O'Neill, Nebraska--In addition to the regular λ recordings by R. Staley, on-the-spot λ measurements were performed during the USAF Great Plains Turbulence Project at O'Neill Nebraska. The purpose of the additional series was to evaluate the regularity of λ from point to point, horizontally and vertically.

For the spot measurements the needle was thrust, at various angles between 30° and 90°, into the surface and vertically through the lower end of a hole, drilled by a sharp-edged pipe. In every case undisturbed soil was hit. Thus λ was measured at depths ranging from 0.5 to more than 80 cm. Temperature increase of the needle during the usable period varied between 0.6 and 16°C. According to the theory, the measured λ actually concerns a cylindrical soil volume of less than 1 cm diameter located around the middle of the needle. Heating currents between 0.2 and 0.5 amp. were used. The rather rough handling of the tiny needles eventually broke the three of them. This was anticipated.

Anything buried or thrust into soil is apt to alter its configuration and, therefore, its λ, by causing air gaps or by compacting the soil. Care was therefore taken to standardize the inserting procedure by mounting the needle in a holder and thrusting it gently into the soil without any side movements.

The test field was a temporarily abandoned cattle pasture, with a soil profile of about one decimeter of loess on gravel sand, followed by gravel below. In a very regular spacing of about 5 cm, small bunches of grass grew, leaving the area in between as a near black, grass-free soil, showing underneath a dense network of roots. In view of the great regularity of this surface build up, a rather small fluctuation of local λ values was expected.

Measurements were made on the dry days, August 7, 8, 9, 13, and 14, and after rain on August 11 and 15, 1953. The local variations found, exceeded every expectation. They are given, therefore, in the form of a frequency diagram (Fig. 2) covering a total of 171 observations. On dry days at 1/2 and 1 cm depth the λ data cover a full power of ten each, their maxima of frequency being at 3×10^{-4} and 11×10^{-4} respectively. On days after rain, data scatter less and show the maximum frequency at 25×10^{-4}. The combined scatter of all data at depths of 5, 10, 20, 27, 40, 50 and 80 cm covers a much smaller field with a maximum frequency at 7.5×10^{-4}.

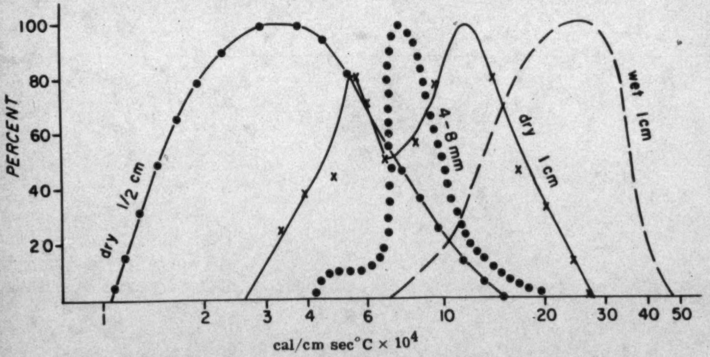

Fig. 2--Frequency of occurrence of local λ values in O'Neill; maximum frequency in each case = 100; Legend on dotted line is 4 - 80 cm; note the high variability in the grown upper layers and the smaller in layers below four cm depth

The total of the values extends from 3 times the value of air (0.5×10^{-4}) to nearly three times the value of water (14×10^{-4}). The systematic variation of local λ data, at any rate, exceeds by far the inaccuracy of the measuring method. No significant correlation to local plant configuration or to the temperature at the point concerned was seen.

Comment--The high variability of near surface λ may be attributed to the natural irregularities of the grass roots. Since our procedure integrates over a spherical or egg-shaped volume of about 1 cm diameter, more variations at even smaller distances may exist. Instruments integrating for a decimeter or so are quite likely to smooth out most of the variances caused by botanical structure.

The consequences for heat flow and soil and plant temperature are obvious. Generally λ will decrease as ρc decreases. This would cause, roughly, an increase of surface temperature variations indirectly proportional to the changes of λ (see (7) of first article), when the outer heat supply suddenly changes.

This fact could contribute to the onset of convection in a sunny morning. With changes of outer heat flow by changes of cloud cover or upper wind, very distinct horizontal temperature pattern near the surface will develop. This could cause initial eddies.

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EVALUATION OF SOIL HEAT CONDUCTIVITY WITH CYLINDRICAL TEST BODIES

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Abstract--Different solutions of the temperature increase with time of a heated cylinder are discussed. This increase depends on cylinder geometry, heat conductivity of the medium, and on the ratio of specific heats of cylinder and medium. For compact cylinders and not too fluffy media, the temperature increase is independent of the heat capacity of the medium. This heat capacity, or the thermal diffusivity, cannot be evaluated using compact cylinders, whereas hollow cylinders or plates yield data of the product conductivity × density × specific heat. The heat transfer coefficient of liquids or gases flowing across cylinders shows a certain observed positive value when forced or free flow vanish. These transfer coefficients are explained as being caused by heat flow from the heated cylinder into a quasi-infinite non-moving medium.

Definitions--The following symbols and terminology are used:

λ = heat conductivity (cal/cm sec deg)
ρ = density (gm/cm^3)
c = specific heat (cal/gm deg)
ρc = volume specific heat (cal/cm^3 deg)
κ = $\lambda/\rho c$ = heat diffusivity (cm^2/sec)
$\lambda\rho c$ = λ^2/κ = surface delay factor (cal^2/cm^4 sec deg^2)
β = heat expansion coefficient (deg^{-1})
μ = viscosity (gm/cm sec)
T = temperature increase of test body (deg K)
t = time (sec)
x = distance from surface (cm)
r, a = radius of cylinder (cm)
z = length of cylinder (cm)
g = earth acceleration (cm/sec^2)
q = heat supply per unit length (cal/cm sec)
Q = heat supply per unit area (cal/cm^2 sec)
h = heat transfer coefficient (cal/cm^2 sec deg)
v = air or fluid velocity (cm/sec)
Nu = $2ah/\lambda$ = Nusselt number
Gr = $8a^3 g\rho\beta(T^* - T)/\mu$ - Grasshof number
α = $\kappa t/a^2$ = Fourier number
Pr = $\mu/\rho\kappa$ = Prandtl number
Re = $2av\rho/\mu$ = Reynolds number
Plain values refer to the soil, those with asterisks (*) to the meter.
y' = dy/dx, $\dot{y} = dy/dt$
δ = $\rho^* c^*/\rho c$
γ = 0.5772 = Euler's constant

$$-\mathrm{Ei}(-x) = \int_x^{\infty} e^{-t} t^{-1} dt$$

$$\mathrm{erf}\, x = 1 - \mathrm{erfc}\, x = 2\pi^{-1/2} \int_0^x e^{-v^2} dv$$

ϕ = any function

Introduction--Permanently installed or temporarily introduced heated cylinders are convenient sensing elements to measure heat material constants in soil and sand in the field. Instruments of this type, therefore, can be used in many studies of atmospheric heat balance and of soil composition and moisture. These relatively simple instruments and the measuring procedures deserve a theoretical estimation of their real value, their accuracy, and their limitations.

The practical importance of thermal material constants--Heat conductivity and heat capacity are not only important parameters in any kind of a heat budget, they may also be used as clues for investigation of composition and structure of material. Moisture content of soil, for example, can be evaluated from thermal data. However, not all measured thermal parameters are equally usable.

According to PATTEN [1909] and to DE VRIES [1952] λ, ρc, and $(\lambda \rho c)$ increase, in a given soil or sand, with moisture content. Variations of these three factors can be used to detect moisture changes. κ shows a maximum at middle soil moisture values, smaller values for high and low moisture. Consequently, κ is of but little value in discussing soil moisture because it may have two identical values at quite different soil moisture values.

In the following, some simple advice is given for the evaluation of these soil thermal parameters using different techniques. The soil is considered as a semi-infinite continuum.

In steady state, the heat conductivity λ determines the heat flow through a certain interface at a given temperature gradient. The temperature variations with time and space in a medium are controlled by the heat diffusivity κ when certain temperature variations are impressed. The heat capacity of a cubic centimeter of soil is ρc and the speed of temperature increase of a plane interface heated at a constant rate increases as $(\lambda \rho c)^{-0.5}$.

Under different experimental conditions the evaluation of these parameters is more or less simple. Some general statements follow:

(a) Elaborate laboratory methods exist to evaluate directly λ or κ or ρ and c. The results, unfortunately, give values only for soil removed from its original condition.

(b) If $\lambda' = 0$ and $(\rho c)^{\cdot} = 0$ or $\kappa' = \kappa^{\cdot} = 0$, the classical method of evaluation of κ from soil temperature records yield interesting data. LETTAU [1949] has shown how for the case $\kappa' \neq 0$, $\kappa^{\cdot} = 0$ some κ data can be found. The solution of the case $\kappa^{\cdot} \neq 0$ is still nearly hopeless.

(c) The surface delay factor $(\lambda \rho c)$ can be evaluated directly by applying known changes in outer heat transfer, for example, by sudden shadowing. This method has been successfully applied to the Moon by BUETTNER [1951a] and LETTAU [1952], and the human skin by BUETTNER [1951b].

(d) Test bodies in the form of spheres, plates, or cylinders may be buried or inserted into the soil. Upon heating, their temperature increases with time, depending on their shape, thermal constants of the instrument and of the soil. ALBRECHT [1932] introduced the use of cylinders to measure λ of soil and VAN DER HELD and VAN DRUNEN [1949] for the λ of liquids. SKEIB [1950] discussed the theory of Albrecht's meter and extended its use for the evaluation of diffusivity κ. DE VRIES [1952] developed more theoretical and experimental details, STALEY and Others [1954] exchanged thermistors for the previously used thermocouples or platinum thermometers to measure the various soil parameters. Most of the formulas of the above papers will be discussed below.

Theory of a cylindrical test body--We will consider a cylinder of diameter 2a, of length b, and of material constants λ^*, ρ^*, c^*. Material constants of the soil are given by λ, ρ, and c. The cylinder is to be heated at the surface with q calories per unit length of the cylinder per second. For the sake of simplicity we neglect the contact resistance of the cylinder. We will assume that the indicated temperature is the true temperature throughout the cylinder. We then write

$$\rho^* c^* \, \partial T/\partial t = \lambda^* \left[(1/r)(\partial/\partial r)\left(r \, \partial T/\partial r\right) + \partial^2 T/\partial z^2\right] + q/a^2\pi \quad \ldots\ldots (1a)$$

for $0 < r < a$, $-b/2 < z < b/2$, and

$$\rho c \, \partial T/\partial t = \lambda \left[(1/r)(\partial/\partial r)\left(r \, \partial T/\partial r\right) + \partial^2 T/\partial z^2\right] \quad \ldots\ldots\ldots\ldots (1b)$$

for $r > a$, $|z| > b/2$. The general boundary conditions are $T = 0$ at $t = 0$.

We now consider five cases, four for solid cylinders and one for hollow cylinders and flat plates.

Case 1-- $a = 0$, $b = \infty$, $\rho^* c^* = \rho c$ which is the situation for an infinitesimally thin wire of infinite length. At a distance r from the wire the following solution has been applied by FISCHER [1939], CARSLAW and JAEGER [1947], and VAN DER HELD and VAN DRUNEN [1949]

$$4\pi T\lambda/q = -\mathrm{Ei}\,(-r^2/4\kappa t) = \ln t + \ln\,(4\kappa/r^2) - \gamma + r^2/4\kappa t - (r^2/4\kappa t)^2/2\cdot 2\,! + (r^2/4\kappa t)^3/3\cdot 3\,! - \ldots \qquad (2)$$

where $\gamma = 0.5772$ (Euler's constant). The solution is applicable for a thermometric device apart from the wire and loses its sense at the wire. It has been used for that very arrangement by VAN DER HELD and VAN DRUNEN [1949] and DE VRIES [1952], however. The partial success of such calculations follows because of the close relationship between (2) and (3b) below.

Case 2--Assume a cylinder of finite radius and infinite length with thermal properties identical to those of the surrounding medium: $a > 0$, $b = \infty$, $\lambda^* = \lambda$, $\rho^* c^* = \rho c$. On the axis of the cylinder the following solution applies [CARSLAW and JAEGER, 1947, p. 223].

$$4\pi\lambda\, T/q = -\mathrm{Ei}\,(-a^2/4\kappa t) + [1 - \exp\,(-a^2/4\kappa t)]\, 4\kappa t/a^2 \qquad (3a)$$

The basic difference between (2) and (3a) is the additional member which indicates the warming up of the cylinder having a finite heat capacity.

Eq. (3a) can be developed in a series as follows

$$4\pi\lambda\, T/q = (1 - \gamma) + \ln\, t - \ln a^2/4\kappa + a^2/8\kappa t - a^4/192\,\kappa^2\, t^2 + \ldots \qquad (3b)$$

From (3a) and (3b) an evaluation of λ and κ seems feasible if enough T/q and t values are measured; however, it will be seen below that while λ may be determined κ the thermal diffusivity, cannot be. Eq. (3b) converges to a straight line on semi-log paper for $t \gg a^2/8\kappa$.

Case 3--If now our cylinder has finite length b, (3a) becomes [CARSLAW and JAEGER, 1947, p. 223].

$$4\pi\lambda\, T/q = (\kappa/a^2) \int_0^t [1 - \exp\,(-a^2/4\kappa u)]\ \mathrm{erf}\,[b\,(4\kappa u)^{-0.5}]\, du \qquad (4a)$$

where $a > 0$, $b < \infty$, $\lambda^* = \lambda$, $\rho^* c^* = \rho c$. Eq. (4a) equals (3a) for large b or small t. For moderate values of $a^2/4\kappa$ the value of the terms within the first bracket in (4a) is proportional to u^{-1}. We assign an arbitrary value of $b(4\kappa)^{-0.5} = 5$ such that

$$T/q \approx \int_0^t [\mathrm{erf}\,(5\, u^{-0.5})/u]\, du \qquad (4b)$$

This reduced integral is shown graphically in Figure 1. The curve is nearly logarithmic for $t < 25$ or $b(4\kappa t)^{-0.5} < 1$ and consequently coincident with (3a). If t exceeds a critical value, therefore, the temperature increase of finite cylinders lags behind those of infinite length. It will be noted that the reduced integral for the assumed value of $b\,(4\kappa)^{-0.5} = 5$ converges to $5\cdot 5$ as t approaches infinity. A sample of the value of the integral for experimental data taken in dry Nebraska soil is also shown in Figure 1. The curve is logarithmic for $1.5 < t < 7$ sec.

Case 4--We next consider a cylinder of infinite length with material constants differing from those of the soil. The conditions are $a > 0$, $b = \infty$, $\lambda^* \gg \lambda$, $\rho^* c^* \lesseqgtr \rho c$ where the asterisks denote the cylinder properties as before. Let $\delta = \rho^* c^*/\rho c$ and $\alpha = \kappa t/a^2$. The solution is given by CARSLAW and JAEGER [1947, p. 284]

$$T\lambda/q = (8/\pi^3) \int_0^\infty \frac{x^{-5}\,[1 - \exp\,(-\alpha x^2)]}{(\delta J_0 - 2J_1/x)^2 + (\delta N_0 - 2N_1/x)^2}\, dx \qquad (5a)$$

where J_p and N_p are Bessel functions of order p of the first and second kind, respectively. Eq. (5a) is, to be sure, valid for $\lambda^* = \infty$. Eq. (5a) has been numerically evaluated by the author for numerous α and δ values; Figure 2 shows the results of such evaluations with α as the abscissa showing different curves for various values of δ. All curves tend to be straight for values of $\alpha > 0.9$. The thermal sensing element used by STALEY and Others [1954], has approximate values of $\kappa = 0.004$ cgs and $a = 0.1$ cm, yielding $\alpha \approx 0.4t$; thus at or beyond $t \approx 3$ seconds one would expect to find a logarithmic relation between temperature and time. The solution for one-dimensional wire is shown by the dashed line in Figure 2. The curve labeled $\delta = 1$ represents the wire having material constants equal to those of soil, and the curve $\delta = 0$ a hollow cylinder.

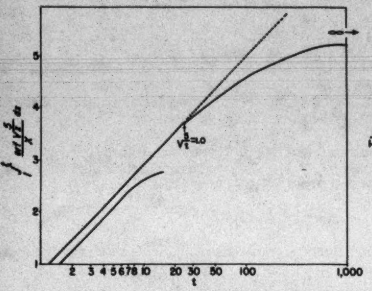

Fig. 1--Relative temperature increase with time t of a thin heated wire of finite length; essential part of Eq. (4); length of the wire is 5 (4 κ); broken line: values for infinite length; lower curve: experimental values recorded by R. Staley, University of Texas

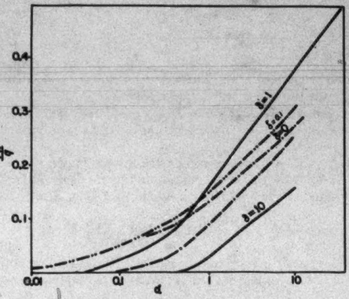

Fig. 2--Relative temperature increase of heated long cylinders of different kind; $\alpha \equiv \kappa t/a^2$; ------ infinitely thin wire, Eq. (2); δ is the ratio of volume specific heat of cylinder to the medium; $\delta = 0$ is a hollow cylinder

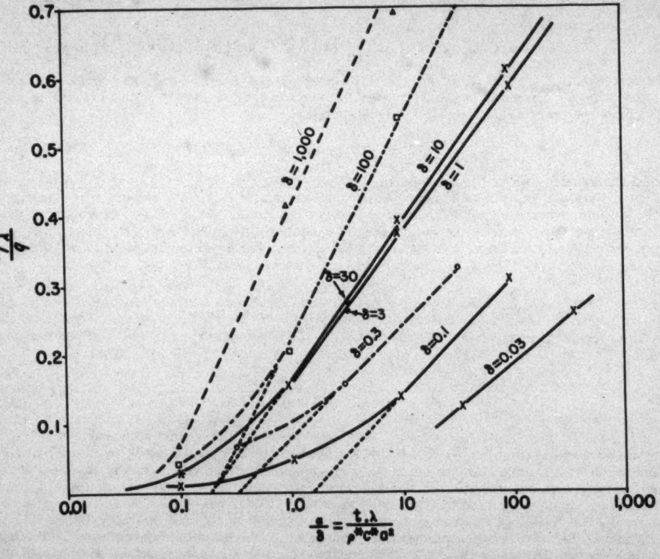

Fig. 3--Relative temperature with time increase of long cylinders for different ratios of specific heats; short dashed line: extrapolated; points: calculated values; asterisk at 0.1: values for $\delta = 1$ and $\delta = 10$ coincide; if λ and q are the same the cylinder temperature rises the faster the thinner the material is (δ large); this speeding up, however, levels off for δ between 1 and 30

In Figure 3 is plotted the ratio α/δ as abscissa against the value of the integral $T\lambda/q$ as ordinate. For each curve δ has been held constant at the value indicated. It will be noted that the quotient α/δ is equal to $t\lambda/\rho^*c^*a^2$, where the expression $\rho^*c^*a^2\pi$ is the heat capacity per unit length for the cylinder and is an instrumental constant. All curves for $1 < \delta < 30$ are nearly coincident, and within these limits, with known $\rho^*c^*a^2$ and measured values of T, t, and q, the thermal conductivity λ may be evaluated. This holds for many cases, since $0.05 < \rho c < 1$ for soil, sand, water, and snow, and $0.4 < \rho^*c^* < 1$ for cylinder materials from ceramics to most metals.

It will be noted that the curves $1 < \delta < 10$ probably bound the region of interest to this study. These curves are logarithmic beyond the value of $\alpha/\delta = 1.0$. To make some estimate of the value of t needed to satisfy the straight line portion of the curve, we take some approximate values of instrument dimensions and material constants. For the above mentioned element, the ρ^*c^* value of 0.6, together with a sensing element radius of 0.1 cm and soil λ of 0.002 gives a value of $\alpha/\delta \approx 0.3\,t$. Thus any value of t greater than about three seconds should fit the logarithmic portion of the curve. This agrees with our findings from Figure 2.

We may write for two points on a given δ curve if $1 < \delta < 30$ and $\alpha/\delta > 1$

$$T_2\,\lambda/q - T_1\,\lambda/q = C\,[\ln\,(t_2\lambda/\rho^*c^*a^2) - \ln\,(t_1\,\lambda/\rho^*c^*a^2)]$$

or

$$\lambda = C\,q\,(\ln\,t_2 - \ln\,t_1)/(T_2 - T_1) \;\ldots\ldots\ldots\ldots\ldots\ldots \text{(5b)}$$

The instrumental constant C may be taken from Figure 3 or from calibration in material of known thermal conductivity. In practice it has been found best for calibration to use materials with heat capacity close to that of the soil so that the calibration ratio $\rho^*c^*/\rho c$ is not greatly different from the conditions met with in use of the instrument. As noted earlier, for dry soil $\delta \approx 2$ and for saturated sandy soil $\delta \approx 1$; but for cork or sawdust $\delta \approx 10$. On the other hand, a material such as gelatin has $\delta \approx 1.0$. Attempts have been made to calibrate a rod in sawdust ($\rho c \approx 0.07$) and other materials of small ρc. Invariably such calibrations have given calibration constants of little practical value in measuring soil thermal conductivity; thus , while in theory the difference between the slope $(T_2 - T_1)/q\,\ln\,(t_2/t_1)$ for $\delta = 10$ and for $\delta = 1$ is not great, in practice it does matter.

In order to use (5b) properly, note that the condition $t\lambda/\rho^*c^*a^2 > 1$ yields $t > \rho^*c^*a^2/\lambda$. Note also that for large t and small a or r the expressions stated in (2) and (3b) may be given in the form of (5b). Large values of t may be used only if the material whose thermal conductivity is being studied is uniform to a radial distance at least r from the center of the sensing cylinder of radius a. This value of r must be such that $r^2 > 4\kappa t_2$ or $r^2 > 4\rho^*c^*t_2a^2/\rho c t_1$. An estimate for this condition may be made from (2). For our instrument r = 0.4 cm in wet sandy soil and r = 0.25 cm in dry soil will satisfy the requirements. It may be noted that if the soil is saturated, the condition of r = 0.4 cm is probably satisfied. As the soil dries, the limit of r becomes less and a smaller homogeneous layer is satisfactory. It is evident, however, that if t_2 is too large, the condition stated above will not be fulfilled. An upper limit for t_2 of about eight seconds would be practical for our instrument. This agrees with the value found from Figure 1.

Another interpretation may be made of Figure 3. For $1 < \rho^*c^*/\rho c < 30$ the temperature of a buried cylinder, cable, or pipe rises with time, independent of the volume heat capacity of the soil and dependent only upon the thermal conductivity λ. The lack of temperature dependency upon ρc means that it is not possible to derive the thermal diffusivity since $\kappa = \lambda/\rho c$.

Case 5--It is of interest to explore an additional solution of (1a) and (1b) that for a hollow cylinder. When $\delta = 0$, (5a) becomes

$$T\lambda/q = (2/\pi^3)\int_0^\infty \left\{[1 - \exp(-\alpha x^2)]/x^3[J_1^2 + N_1^2]\right\}dx \;\ldots\ldots\ldots\ldots \text{(6a)}$$

For large values of x the integral simplifies to $\pi\,[1 - \exp(-\alpha x^2)]/8x^3$, and (6a) becomes

$$T/q \;\propto\; \lambda^{-1}\,\kappa^{0.5}\,\phi\,(ta^{-2}) = (\lambda\rho c)^{-0.5}\;\phi(ta^{-2}) \ldots\ldots\ldots\ldots\ldots\ldots \text{(6b)}$$

A similar equation holds for a buried flat plate

$$T = Q\,(t/\pi\lambda\rho\,c)^{0.5} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(7)}$$

where Q is the heat supplied per unit area. Note that in the case of both the heated hollow cylinder and the heated flat plate, the quantity $\lambda\rho c$ may be evaluated, but not thermal conductivity alone. It would appear advantageous to explore the possibility of devising an instrument which would measure both λ and $\lambda\rho c$ simultaneously in natural soil. With sufficiently accurate and representative values of each of these quantities, it might be possible for the first time to measure soil heat capacity in situ.

We have dealt thus far only with the notion of using the portion of the temperature - time curve during the heating process. The cooling period after the heating current has been turned off can also be used to determine λ or $\lambda\rho c$. If $q = q_o$ for $t < t_3$ and $q = 0$ for $t > t_3$, we add a negative heat source $-q_o$ to the existing one for $t > t_3$. The solutions generally are

$$\left.\begin{aligned} T\lambda/q &= \phi(t) \quad t < t_3 \\ T\lambda/q &= \phi(t) - \phi(t - t_3); \; t > t_3 \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots (8)$$

Convective and advective heat transfer--Water and air, or any other liquids or gases may increase the effective heat loss by either advection or convection. The first term concerns a flow due to outer sources, such as water seeping through sand or air blowing through porous soil. Convection is the buoyant movement of liquid or gas caused by temperature difference induced density differences. For not very small distances of the pores, sand grains, etc., radiation transfer has to be considered also.

Convective and advective heat transfer around cylinders are generally treated using a heat transfer coefficient h. It is often assumed that the temperature at some distance does not react to the heating element, or in other words, that a steady state of T is achieved after a finite time. As (2), (3), (4), (5), and (6) show, this does not hold for heated cylinders in a solid. However, an approximation for large t might help.

Experimental data of 'free' convection in liquids and gases can be summarized by

$$Nu = \phi(Gr \cdot Pr) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

ϕ is usually described as fourth root for large Gr and as a constant for small Gr. The NUSSELT [1922] and DAVIS [1920-25] experimental data for heated horizontal cylinders can be completely described by

$$\left.\begin{aligned} Nu &= Nu_o + 0.52\,(Gr \cdot Pr)^{0.25} \\ Nu_o &= 0.420 \qquad 10^{-5} < Gr < 10^{5} \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (10)$$

Nu_o concerns heat transfer conditions with $Gr = 0$. This case is actually realized in a solid where viscosity $\mu = \infty$. The most important experiments for small Gr numbers are made by DAVIS using a heated wire in liquids. We may use his data and assume $Gr = 0$.

Then, (3) becomes applicable and may be combined with the definition of the Nusselt number.

$$Nu_o = \frac{h2a}{\lambda} = \frac{q2a}{2a\,\pi\,T\lambda} = \frac{q}{T\lambda\pi} = 4/(1 - \gamma + \ln t - \ln\,(a^2/4\kappa) + \ldots) \quad \ldots (11)$$

If we insert Davis' values, $2a = 0.0155$, $\kappa \sim 0.01$ (liquids), $t \sim 200$ sec; $Nu_o = 0.4$ results. This is in best possible agreement with the observed values 0.42. This value, however, cannot be called a constant since it will vary slightly with the experimental conditions, namely t, a, and κ.

Similar considerations hold for advection or 'forced convection.' Data for flow of gas across cylinders are best represented by McADAMS [1942]

$$Nu = Nu_o + 0.43 \cdot Re^{0.52} \qquad 10^{-1} < Re < 10^{3} \quad \ldots\ldots\ldots (12)$$

In this case $Nu_o = 0.32$. The difference between this value and the one above, ($Nu_o = 0.42$) is, probably, due to the experimental arrangement.

The above treatment can be considered as a satisfactory first approximation to the problem of heat transfer in porous flooded media. In a rigorous calculation members of the form $\rho c v T'$ have to be added to the initial differential equations. Obviously, for very slow, but not vanishing motions or small Gr or Re, the conduction term Nu_o will not be independent of motion, and the motion terms containing Gr or Re will not be independent of λ.

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TRANSMISSION OF MICROSEISMS ACROSS NORTH AMERICA AND THE WESTERN NORTH ATLANTIC

Dean S. Carder

Abstract--A comparison of microseisms recorded at Bermuda and North American stations indicates that the North Atlantic between the continent and Bermuda has a relatively high absorption rate for microseisms having periods of ten seconds or less. If the source area is on the margin of the continent and the period on the continent is 6.5 to nine seconds, energy absorption over a 1000-km oceanic path is probably at least an order greater than over an equal continental path, and absorption rates of the longer periods are relatively less. The oceanic passage is accompanied by a slight increase in period. All four- to five-second microseisms recognizable on the Bermuda Milne-Shaw records are believed to have local sources.

Introduction--The relative abilities of the North American continent and that portion of the Atlantic Ocean between North America and Bermuda, to transmit certain microseisms, will be discussed in this paper.

It was found earlier that microseisms appearing simultaneously at Bermuda and continental stations may have a common source [CARDER, 1952, 1953, 1954]. If this source is on the margin of the continent, the amplitudes at Bermuda are relatively very small.

There is also some evidence that attenuation of the shorter periods, say four or five seconds, over an oceanic path is greater than of periods from seven to ten seconds, because there is no definite evidence that four- to five-second Bermuda microseisms have other than local sources. This statement is difficult to verify because the dominant normal period at Bermuda is four to five seconds and whatever proof that is available must be in the negative direction. This was furnished in one case on January 7, 1950 when a cold front moved oceanward off the Atlantic Coast. Heavy four-second microseisms were recorded at Washington, D. C., and weak four- to five-second period waves appeared as riders on longer waves as far west as Bozeman, Montana. There were no such riders discernible on the longer period activity at Bermuda until sometime later when local weather was favorable for producing them.

Nevertheless, four- to five-second microseisms are quite common at Bermuda. In another paper, it will be shown that if they are large enough to rise above the normal background they may be assigned to local sources. Furthermore, it will be shown that fast moving hurricanes approaching the island do not produce above normal four- to five-second microseisms until the storm center is within one or two hundred miles of the island, and the nearest limb of the hurricane is much closer than this. Of 13 hurricanes under study, in every case where above normal four- to five-second microseisms appeared they could be explained as having a local origin.

In regard to slightly longer periods, there is evidence that weak six- to seven-second Bermuda microseisms may have sources outside of the local area. Of the 13 hurricanes under study, there was at least one case of amplitude parallelism of 6 to 6.5 sec microseisms with the nearest approach and strengthening of winds in a hurricane 450 mi to the southeast. There are also other evidences of fairly distant sources for this period range, but in every case the microseisms are weak.

Periods of seven seconds or greater can often be traced to regional or distant sources, but their amplitudes rarely rise above two or three microns.

During the interval from August 1, 1948 to January 31, 1951, April to July of each year excluded, 14 groups of seven- to ten-second microseisms were observed from a routine search of Bermuda Milne-Shaw records, and two other groups were found as a result of a re-examination of the records. Doubtless other groups having normal or subnormal amplitudes were overlooked. Of these 16 groups, one had double amplitudes of 6 μ and was assigned to a nearby hurricane. One group with ten-second periods and 2.5 μ amplitudes could be traced to a violent storm on the coast of Alaska. Three groups

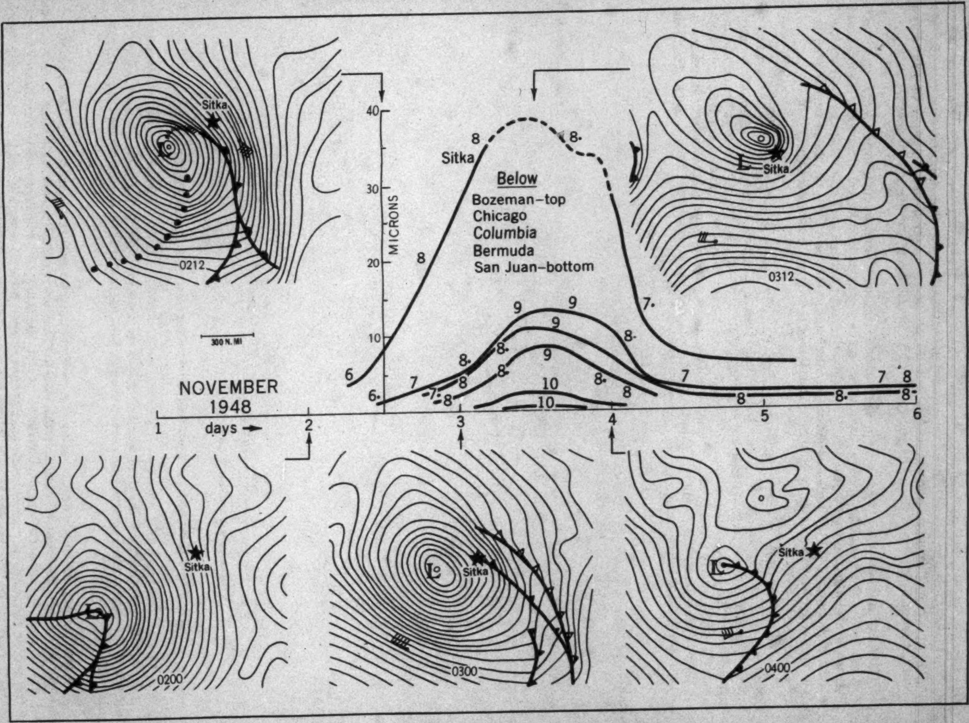

Fig. 1--Data relative to the storm of November 1-3, 1948 with seven-second periods and 2 μ amplitudes were probably traceable to a heavy storm on the Newfoundland banks, and another had a doubtful origin. Of 8 groups with 7.5- to nine-second periods and 1 μ amplitudes, one could be traced to the Alaska coast, one probably to Newfoundland, one to either the North Atlantic near Greenland or Alaska, and five had doubtful sources. Of two barely perceptable groups of waves with seven- to 7.5-second periods, one group was traced to a violent storm off the coast from Oregon to British Columbia and the other was doubtful.

The doubtful cases and very likely other cases not considered doubtful could very well have been caused by the mingling of ocean swells set up by opposing winds at a time when storm conditions were not necessarily evident. This was particularly true of one case of heavy local microseisms on January 1-3, 1949 (discussed in another paper), where it will be shown that moderate winds in the area were favorable to the production of oppositely moving swells.

Heavy microseisms traced to a West Coast storm of November 1-3, 1948 will be used to illustrate the relative attenuation over land and oceanic paths. This storm and its effects were very little different from perhaps a dozen or so others that follow a like course each year, except perhaps it was more violent than most. Copies of surface charts are reproduced in Figure 1, together with a time-amplitude plot of concurrent microseisms as recorded by scattered seismographs as far away as San Juan, Puerto Rico. Dominant periods are numerically represented. A plot of distance against amplitude maxima is represented in Figure 2.

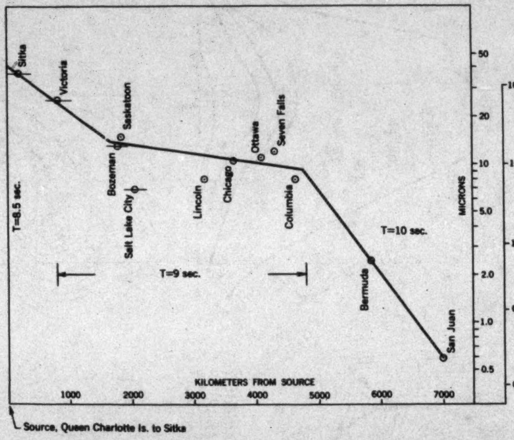

Fig. 2--Attenuation of amplitude and energy of microseisms originating from storm of November 1-3, 1948

It should be noted from the first weather chart on November 0200 (second day, zero hours, GCT), that while the storm is entirely at sea, even though it is violent, there are no out-of-usual microseisms.

Above normal six-second microseisms were first noticed at Sitka and Victoria about 0206, eight hours before the front had reached the coast. They were still weak on 0212, one or two hours before the front had reached Queen Charlotte Island. On 0300, Figure 1c, the storm center was offshore but the front had passed inland. Microseismic amplitudes were continuing to increase, reaching their peak on 0312, when the storm center was passing over Sitka. The storm by that time had materially weakened. On 0400, the microseisms were still heavy, continuing another eight hours (in fact another 48 hours at Bozeman and Chicago), but the storm which indirectly had caused them had broken (Fig. 1e). It seems improbable that the relatively weak low shown offshore on 0400 was responsible for the continued microseismic activity when the much more violent storm failed to produce any when it was in the same area 48 hours earlier. This is a continuing pattern of more than a score of other such storms that have been investigated. As was pointed out in earlier papers it seems apparent that the microseisms were produced not by the storm itself, but by effects of the storm.

From Figure 1, it is quite evident that microseisms generated by the storm effects doubtless traveled across land and under the sea as far as San Juan, Puerto Rico, 7000 km away. The time-period-amplitude parallelism at all stations cannot be coincidence, especially since this parallelism is repeated time and again; although usually on a lesser scale.

Over the first few hundred kilometers of the initial continental crossing, the period increased from 8.5 seconds to nine seconds and remained constant from then on. Likewise, there was an apparent additional period increase to ten seconds over the first thousand or so kilometers of Atlantic travel, but no increase beyond that.

Ragged 8.5-second periods appeared in local background at Honolulu at the time of the continental microseisms. If the two groups had common sources there was no evident period increase over the sub-Pacific crossing.

The amplitude-distance plot in Figure 2 contains data from the Canadian stations kindly furnished us by William G. Milne. There is an apparent rapid decrease in amplitude over the Cordilleran crossing. Salt Lake City seems to be in a relatively quiet spot from a viewpoint of West Coast microseisms.

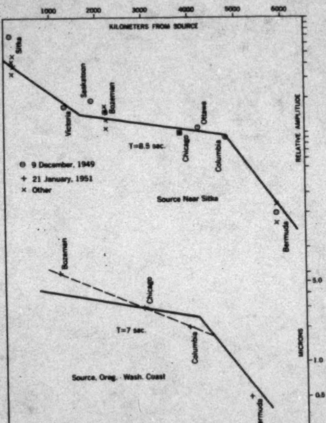

Fig. 3--Amplitude attenuation of microseisms originating on the West Coast; solid lines reproduced from Figure 2

Attenuation across the northern Great Plains area is very low. From Saskatoon to Ottawa and Seven Falls energy attenuation is less than linear. However, if data from Lincoln and Columbia are added, energy attenuation is about linear, that is, energy falls off about as the first power of the distance. It has long been recognized that attenuation across the Canadian Shield and the central and eastern United States is very low. This fact is a serious deterrent to optimum recording of teleseisms in the entire area.

From the evidence of Figure 2 alone, energy attenuation for each thousand km across the North Atlantic is about an order greater than for a like distance across the Canadian Shield.

Several possible explanations for this have been advanced. The most valid seems to be the continuity of a low-speed layer beneath the Canadian Shield, either at the surface or at some depth in the crust, in which the microseismic energy is trapped, and the relative lack of such a layer beneath the ocean. Mountain structure and the discontinuities at the edge of the continents would tend to dissipate the energy. However, microseisms having Pacific origins have had as much success reaching Bermuda as those originating near the continent in the Atlantic, indicating either that the ocean bottom structure as well as the continental marginal discontinuity absorbs microseisms or that microseisms do not originate in deep water. Another explanation for the rapid absorption rate under the oceans is related to the idea that microseismic periods have some dependence on the depth of the water. Assuming that microseisms are Rayleigh waves, there is a vertical component which is damped out by the overlying water except for the special cases where the depths are such as to permit accoustic resonance.

The graph of Figure 2 is reproduced in shape in the two cases shown in Figure 3, and microseismic data from other West Coast sources are applied to it, using Chicago as a reference. On the basis of the more complete data, it appears that the shorter the period the greater the attenuation across the continent. It must be noted that the storm of November 1-3, 1948, was an ideal test case because of its violence together with a timing when background from other sources was relatively quiet. Furthermore, trace amplitudes on the Bermuda Milne-Shaws and the Columbia McComb-Rombergs are very small in the case of lesser microseisms and accuracy of measuring relative amplitudes is rather coarse. However, there is little doubt of the relatively rapid attenuation over the Atlantic path.

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U. S. Coast and Geodetic Survey
Washington 25, D. C.

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MICROSEISMS AT BERMUDA

Dean S. Carder

Abstract--From and examination of above normal microseisms recorded on the Bermuda Milne-Shaw seismograph over several hurricane and winter seasons, it was found that in all cases, if the periods were 4 to 5 seconds or if the microseisms were strong, they could be attributed indirectly to local weather conditions. Occasionally weak 7 to 10 second microseisms could be traced to storm conditions from as far away as the coast of Alaska, but absorption of all microseisms across the northwest Atlantic is relatively high. Strong microseisms may be generated when local storm conditions are not apparent but when the wind is favorable for the production of opposing swells.

Introduction

In a current paper [CARDER, 1955] it was shown that seven- to ten-second microseisms having a distant source may be weakly recorded on an oceanic island such as Bermuda if source conditions are favorable, but that the attenuation rate across the ocean is very high compared with the rate across eastern North America. It was also pointed out that no evidence could be found where four- to five-second microseisms recorded at Bermuda had other than local sources. In the present paper the source possibilities of microseisms recorded on the Milne-Shaw seismograph at Bermuda will be examined and the apparent inability of the western North Atlantic to transmit them in strength will be given a more exhaustive test.

The seismograph stations at Bermuda and Chicago are nearly equidistant from the Atlantic coast line, so that the relative strength of microseisms traceable to a common source on the continental margin should indicate the relative ability of the ocean and continent to transmit them. Both stations are equipped with displacement-type seismographs and the records through January 1951 are stored in the files of the U. S. Coast and Geodetic Survey in Washington. Table 1 lists the instrumental constants at the two stations.

Table 1--Instrumental constants

Station and components	Organization	Instrument	Drum rate	Period	Magnification
			mm/min	sec	
Bermuda EW NS	Meteorological Sta. and International Union of Geodesy and Geophysics	Milne-Shaw	8	12	250
Chicago EW NS	University of Chicago and U. S. Weather Bureau	McComb-Romberg	15	10	335

Records from the two stations covering three fall and winter seasons from 1948 to 1951 were searched for microseisms that rose above the normal backgrounds. When found their amplitudes and dominant periods were measured at frequent intervals. No waves were measured unless they were contained in frequent groups of at least four waves each. Periods when measured were estimated to the nearest 0.2 sec and the trace amplitudes were estimated to the nearest 0.1 mm. Because of the low magnifications and the slow drum rates, wave form analyses were not attempted.

All weather data used in this study were taken directly from the U. S. Weather Bureau surface charts.

Microseisms at Chicago and Bermuda, season 1948-1949

Amplitudes and dominant periods are plotted according to time in Figures 1 and 2 together with appropriate wind and frontal conditions near Bermuda. The position of a front, low, or wind flags are numbered according to day and hour, the first two digits representing the day and the second two, the hour. All times are in GCT.

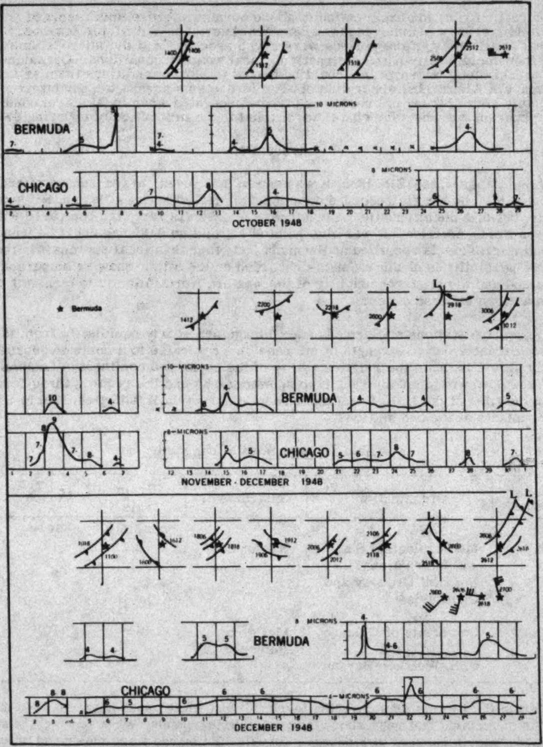

Fig. 1--Microseisms at Bermuda and Chicago, October 2 to December 28, 1948; Bermuda is represented as a star on a five-degree grid; the numerals on the grid are days and hours, GCT; the numerals on the amplitude graphs are the periods in seconds; an appended dot an additional half second

From a close inspection of Figures 1, 2, and 3c, all above normal 4 to 5 second Bermuda microseisms may be explained as resulting from the passing of a warm front, a cold front, a secondary low, a hurricane, or a nearby extratropical storm. Usually, but not always, the amplitude increase starts from the passing of a front, and often with a reversal of wind direction. Some cases of wind reversals are shown on the charts. All passages of fronts are not necessarily associated with an amplitude increase but usually when this happens, the background is already somewhat above normal

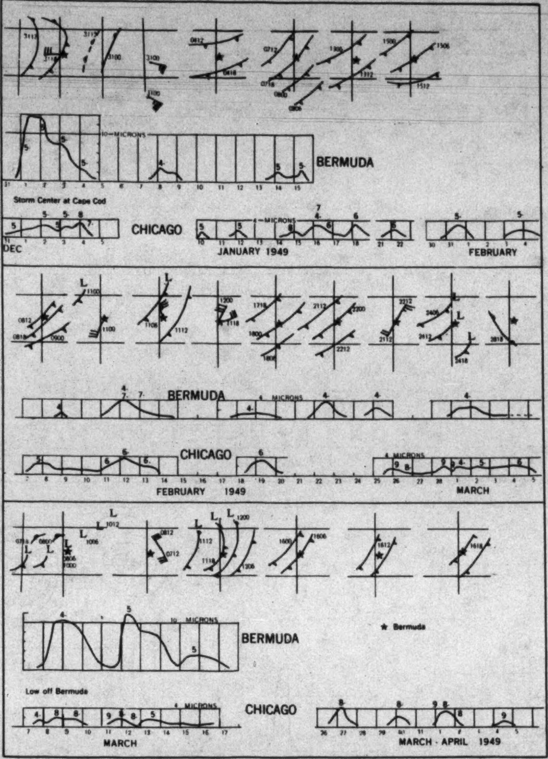

Fig. 2--Microseisms at Bermuda and Chicago, December 31, 1948 to April 5, 1949; see note on Figure 1

as a result of earlier activity. Often microseisms continue for several tens of hours after the weather which apparently was indirectly responsible for them has moved on, or has dissipated.

In general, Chicago and Bermuda microseisms, in point of time and period, do not coincide, but there are exceptions which will now be discussed.

Bermuda microseisms from a North Pacific storm, November 2 - 4--This group was discussed in some detail in a current paper [CARDER, 1955]. The source was on the coast of Alaska and British Columbia.

November 1418 to 1520 (14th day 18th hour to 15th day 20th hour)--A cold front passed Bermuda about 1410, 24 hours before the amplitude maxima. At 1500 a storm moved off Newfoundland which probably was responsible for the activity at Chicago. The Bermuda microseisms certainly cannot be definitely traced to the same source.

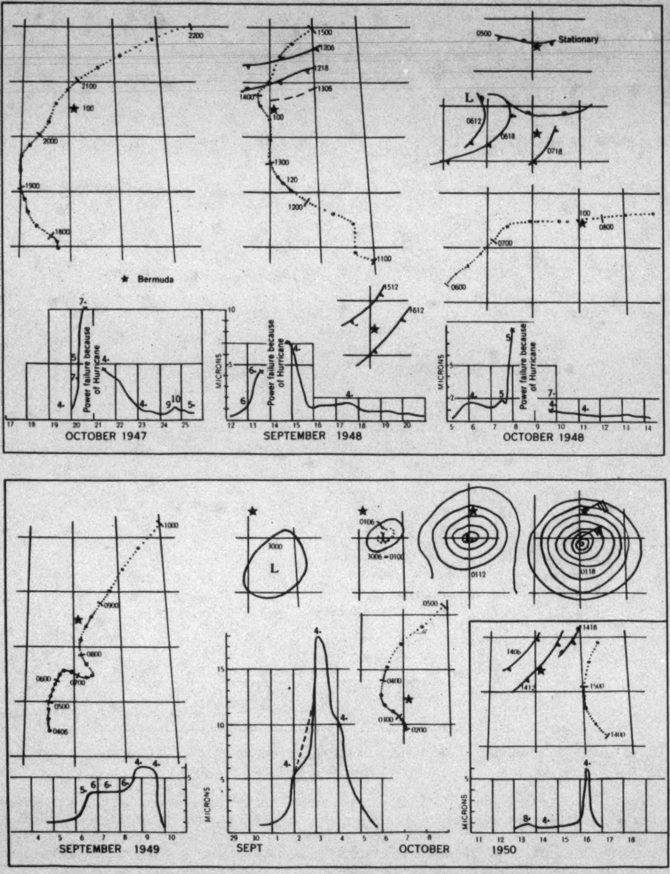

Fig. 3--Microseisms at Bermuda, hurricane tracks, and other weather conditions on a five-degree grid; four digit numerals are days and hours GCT; two and three digit numerals are central wind speeds in knots

December 0500 to 2812--During this time, some parallelism at Bermuda and Chicago existed, but all of the Bermuda microseisms can be traced to local conditions. While the same storms may also have been responsible for some of the Chicago microseisms, the source area usually can be traced to the continental margin.

February 1100 to 1400--The 6.5-second microseisms at Chicago and the 7.5-second microseisms at Bermuda may have a connection with the same fairly violent storm which at 1206 was centered about 250 miles southeast of Newfoundland. The four- to five-second microseisms at Bermuda can be traced to local sources.

March 0712 to 1712--The first of a triple peak at Bermuda was definitely associated with a storm that hovered over Bermuda at this time and the second peak probably with the passage of fronts and accompanying wind reversals and continuing sea wave action after the storm had passed on. The third peak is probably associated with a passing front. The eight- to nine-second Chicago microseisms may possible have originated from storm conditions near Bermuda, but if so, parallel microseisms at Sitka having the same periods but greater amplitudes are difficult to reconcile.

Bermuda microseisms recorded from October 1, 1949 to March 31, 1950 and from October 1, 1950 to February 1, 1951, have been measured and checked with the weather in a similar manner as above outlined. No change in general results was noted.

The study thus far implies that in general, six- to ten-second Bermuda microseisms strong enough to rise above the normal background may be attributed to distant sources, but in these cases, they are always weak. The latter groups may be recognized because of the longer periods, not necessarily because they rise above the local background.

A direct correlation of heavy microseisms to conditions favorable to setting up of opposing swells

As noted in the top of Figure 2, very heavy and long enduring microseisms were recorded at Bermuda beginning late December 31, 1948 and continuing through January 4, 1949.

An eastward-moving front passed Bermuda at the time when the amplitudes began to increase. This of itself is not a sufficient cause for what followed since the passages of other fronts were associated with much smaller amplitudes. Nor could the heavy microseisms be directly attributed to a nearby extratropical storm. The reproductions of surface weather maps shown in Figure 4 tell why.

Two extratropical storms are illustrated in Figure 4. Of the two storms the first one would be expected to produce the heaviest microseisms since it was closer and more violent than the other. Yet on December 2012, the time of the first storm, Bermuda microseisms were hardly above normal, not counting the sharp peak about 1922 because of obvious local activity. The second storm and the heavy microseisms in question were concurrent. If the storm were the cause, microseisms at Chicago likewise would have been very heavy since the distance was about the same together with an added advantage of an all land path, since the storm was moving oceanward off Cape Cod at the time. The Chicago microseisms were above normal, but no more so than would be expected from a storm of this character, considering its position on the continental margin.

It remains that we cannot always truthfully say 'Here are heavy microseisms, there is a violent storm, therefore the storm causes the microseisms; and since the storm is 600 mi away, heavy microseisms will travel that far,' in this case under the ocean. The cases of the storm on December 20 and of certain hurricanes discussed later deny that heavy five-second microseisms will travel more than a small fraction of that distance under this part of the ocean. A closer examination of local conditions therefore is necessary.

On December 3100 the Weather Bureau mapped a warm front moving slowly westward about 300 mi east of Bermuda (see Fig. 5). Three hundred miles behind this front moderate easterly winds were observed and plotted. The weather map indicated that the front was vanishing on 3112. At the same time an east-moving cold front was approaching Bermuda. The cold front was moving before moderate westerly winds. Here is a case where heavy microseisms were generated at a time when conditions were ideal for the production of east-moving ocean swells west of the island and west moving swells east of the island, such that they would mingle in the neighborhood of the island concurrently with the appearance of the heavy microseisms. Furthermore, these swells probably continued to move one or more days after the atmospheric conditions which produced them had dissipated. It is to be noted again that these are the heaviest non-hurricane microseisms of the period under study, and they were produced when violent weather was not in evidence.

Other cases where the mingling swells are not entirely oppositely directed are not so ideal and the resulting microseisms are not so large.

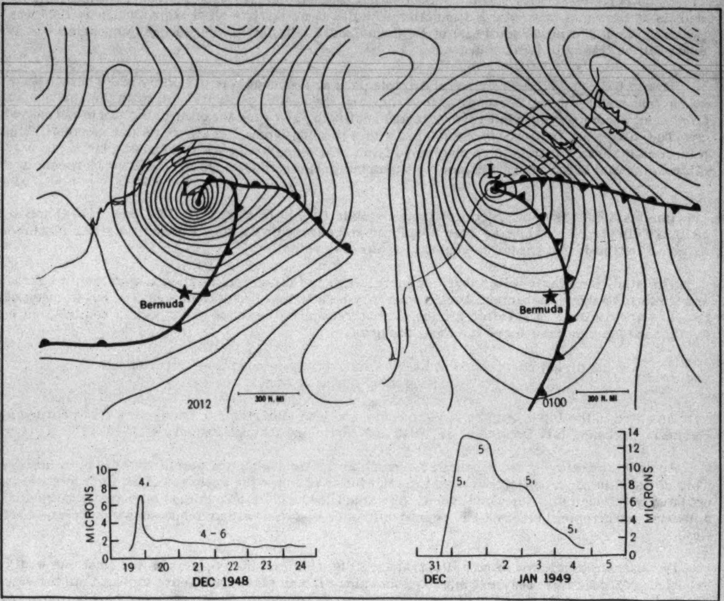

Fig. 4--Extratropical storms of December 20, 1948 and January 1, 1949, and concurrent microseisms at Bermuda

Hurricane microseisms at Bermuda

Attention will now be given to microseisms at Bermuda attributed to hurricanes or while hurricanes are in the West Atlantic. Earlier views [for example, GILMORE, 1952, and RAMIREZ 1939] that Bermuda may receive microseisms originating directly from the hurricanes, will be tested.

Data covering four hurricane seasons from 1947 through 1950 together with hurricane paths and other pertinent weather information are presented in graphical form in Fig. 3 and 6. Arrangement is according to type cases rather than chronology. The storm paths which were taken from Weather Bureau Surface Charts are in fair but not perfect agreement with storm paths presented in reports assembled by the U. S. Naval Air Station in Miami, Florida. Available hurricena wind speed information taken from the latter reports have been inserted in their proper places.

Figure 3--Each of the first three hurricanes indicated in Figure 3 contributed to power failure at Bermuda. In Figure 3a, weak above-normal microseisms began to appear on 1923 (19th day 23rd hour) when the storm center was about 225 (nautical) miles from Bermuda, but the effective part of the hurricane, namely the limb moving toward the island, was much closer than this. Heavy microseisms began to appear about six hours after the initial onset at which time the forward limb of the storm was on the island; and 12 hours after the initial onset, high winds caused a power failure. Two days after the power failure, the storm center had moved 1000 miles beyond Bermuda, and its force was abating. Although, microseismic amplitudes were diminishing they were still somewhat higher than when the storm was approaching the island less than 250 miles to the south.

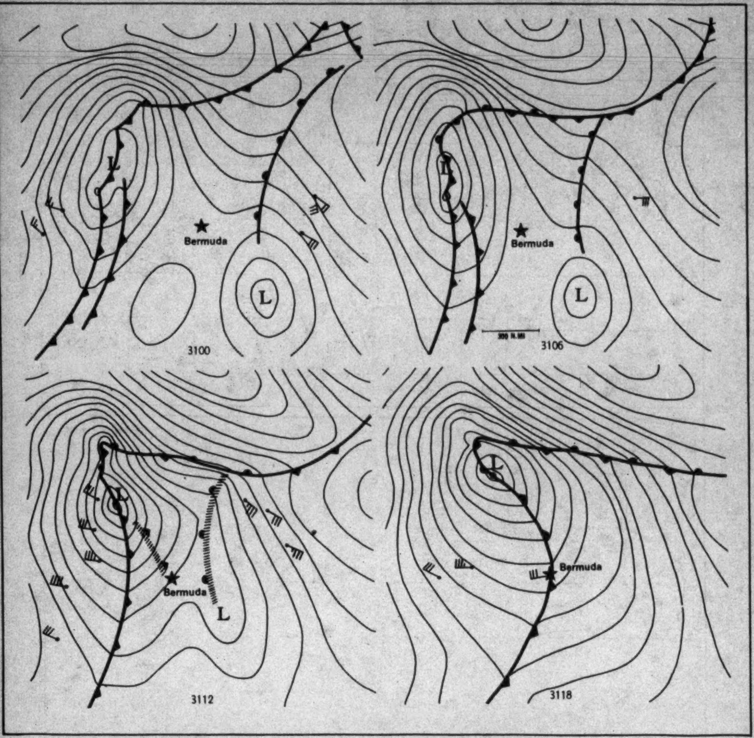

Fig. 5--Weather conditions near Bermuda on December 31, 1948

Using evidence from this storm alone, if the microseisms generated as a result of a hurricane originating from under the storm center, or from under the area covered by winds having a certain minimum velocity, they do not travel in force more than 200 mi or so beneath the sea; and this certainly is not the only source of such microseisms, otherwise they would die out as rapidly while the storm is receding, as they build up while the storm is approaching the island.

On the other hand, if microseisms are generated by mechanical processes which are independent of, but are set in motion by the storm, and which continue in motion long after the causative force, in this case the storm, has passed on, then the microseisms would continue as long as these processes continue in motion, in this case at least three days. The ocean swell idea advanced by LONGUET-HIGGINS [1950] and verified in part by KAMMER and DINGER [1951] is a mechanical process that can be set up in this way and which can continue for several days. Evidence from this hurricane alone, therefore, strongly supports the Longuet-Higgins ideaa that the ocean swell is an important generative process of microseisms.

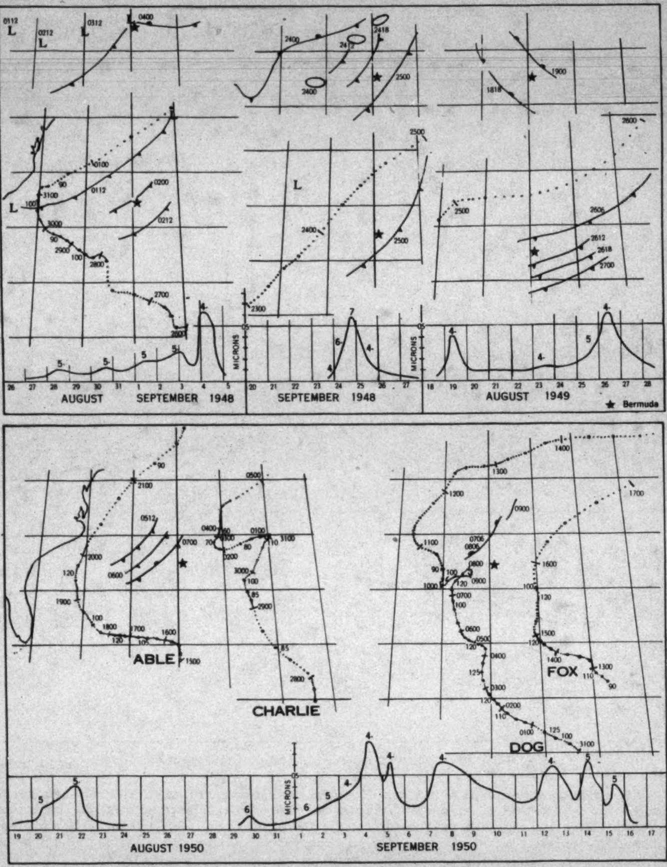

Fig. 6--Microseisms at Bermuda, hurricane tracks, and other weather conditions on a five-degree grid; four digit numerals are days and hours GCT; two and three digit numerals are central wind speeds in knots

An alternative viewpoint that a microseismic barrier may exist south but not north of Bermuda has come to my attention. The failure of the strong extratropical storm indicated on the weather map in Figure 4, centering 500 mi north of the island, to produce microseisms indicates the presence of a barrier north of the island also. It is the opinion of this writer that the introduction of microseismic barriers to explain anomalies has been overworked in the past. Wind speeds at Bermuda during the height of this storm were reported by the Weather Bureau to be in excess of 100 mph.

In Figure 3b, the weak six-second microseisms late on September 12, may have originated from near the storm area and had traveled 400 mi beneath the ocean to the island. It is also possible that the fetch from an advancing cold front and a weak but high speed fetch from the hurricane both of which had outrun their causative forces may have met somewhere near Bermuda.

Beginning about 1304, the strong microseisms were definitely local and the period was still six seconds. Heavy microseisms continued two days after the storm had passed, again showing an origin other than the storm area. A passing front contributed to the group beginning about 1600.

Air reconnaissance reported 120 knot winds at 1212 but there was no information after that. As the storm passed over Bermuda, the winds exceeded 100 mph, causing great damage.

In Figure 3c, microseisms definitely attributable to the hurricane began on 0716 as a limb of the storm began to envelop the island and only seven hours before power failure. There is no support here for transmission under the sea over distances greater than 100 or 200 mi, assuming that the source was beneath the storm area. The activity before 0716 can be attributed to passing frontal systems. The weak 7.5-second periods following resumption of power may possibly have had a source near the storm which by now had become extratropical in character off Newfoundland 1000 mi to the northeast. As this storm passed over Bermuda, winds in excess of 100 mi/hr were experienced.

In the cases of Figures 3d and 3f, the storms were rapidly moving and in each case high winds on the forward limb of the storm began to envelop the island before microseisms definitely attributable to the storm began to appear. In these cases, the storm outran the swell, assuming that the swell was responsible for the microseisms. On the other hand, using the same assumption, if the storm is moving slowly, the swell will outrun the storm, and microseisms will appear relatively early. Such is the case of Figure 3d.

In this case, it may be argued that because the plateau in the amplitude curve began at 0612, identically in time with a sudden deviation of the storm toward the east, we have definite proof that the source was under the storm area. If this is so, the continuation of the amplitude increase should then have begun on 0712 when the storm began again to move toward the island, instead of nearly 24 hours later. Furthermore, at this time, according to the ZOCH, [1949], 'By the afternoon of September 7th (0720) it had become a hurricane of great size and severity.'

The storm track passed to the right of the island, and the island got the full force of the storm at the time of passage, because before this time, the winds on the nearest limb were blowing the wrong way. The relatively low-amplitude peak was reached at this time and continued until the storm center had receded 500 mi when the amplitudes began to diminish.

Figure 3e shows the strengthening of a tropical storm about 150 mi south of Bermuda. Resulting microseisms are represented graphically. They reached a high maxima at the height of the storm over the island and continued two days with diminishing amplitudes.

The sharp peak on 1506 shown in Figure 3f possibly may have had a source under the storm center, but it can also be explained from a local merging of fetches from the hurricane and a dissipating front.

Figure 6--The hurricanes represented in Figure 6abc are indefinite contributors of Bermuda microseisms. In every case, the high amplitude peaks are caused in connection with passing fronts or secondary lows, with perhaps some contribution from the hurricanes. The hurricanes were probably responsible, in part at least, for weak microseisms represented elsewhere on the graphs, but of themselves, they give no definite answer to our problem.

In the case of the hurricane of August 26 to September 1, 1948 (Fig. 6a), 100 knot winds were reported by air reconnaissance on the afternoons of August 28 and 30th, coincident with small microseismic peaks; and the peak on the 28th was almost coincident with the closest approach. The time lag here was about 12 hr or about 36 hr behind an earlier position of the storm when it was 500 mi south of Bermuda. Since this hurricane remained nearly the same distance from Bermuda for more than four days, association of microseismic peaks with hurricane position or even with wind strength at a particular time is not conclusive.

Four hurricanes contributed to Bermuda microseisms during the 30-day period covered by Figure 6d. Two of the hurricanes passed to the left of Bermuda and in the early stages of the nearest or fast-moving limbs contributed to Bermuda-ward swells. The other two passed to the right and swells from the nearest or slow moving limbs were oppositely directed. This may be a partial explanation of why the peak on 2012 to 2300 was somewhat larger than on 3000.

The ability of the sea floor to transmit microseisms will now be tested, using the evidence from these hurricanes alone.

The amplitude maxima on August 2200 lagged more than 30 hours behind the nearest approach of Hurricane Abel allowing plenty of time for the hurricane-generated swells to reach Bermuda.

However, the weak six-second microseisms from 2912 to about 0200 may have originated from under the storm area of Hurricane Charlie because the amplitudes increased slightly as the storm approached the station and diminished as it receded. In this case, there was no time allowance for a hurricane-generated swell to reach the island, besides the islandward limb was moving in the wrong direction. Later than 0212 this argument no longer is valid because on 0212, the storm had its closest approach. It then receded, at first slowly, then rapidly, yet the microseismic amplitudes continued to increase, reaching a maximum 48 hrs after the approach of the storm. At this stage of the storm's history, the westerly limb of the storm was NNE of Bermuda producing SSW moving swells. Several days earlier than this the slow moving Hurricane Dog was coming in from the south, and the fetch from it had a chance to reach Bermuda. The oppositely directed waves from the two storms were probably responsible for the high maxima on 0410 and the lesser maxima on 0510. Later than 0412, the contribution from Hurricane Charlie dwindled, with an accompanying decrease in the microseismic amplitude even though the north-moving fetch from Hurricane Dog was probably continuing.

On 0700, a southeast-moving frontal system became a contributing factor and another maximum was in the making. On about 0712 Hurricane Dog started to move northeasterly as if to pass just north of Bermuda, and it may be argued that this was the cause of the near coincident amplitude increase, pointing to a near-the-storm origin. This would have been a valid argument were it not for the front, which incidently may have caused the storm to change its direction shortly after 0800. Continuing cross currents following the wake of Hurricane Dog as it moved west and north of Bermuda may have been responsible for amplitude peaks on 1218 and 1410. Hurricane Fox also may have contributed to the peak on 1514 which incidentally came 12 hours before the nearest approach of Hurricane Fox.

Periods of hurricane microseisms

Reference is made to DONN [1954], KAMMER and DINGER [1951], and PRESS and EWING [1948]. Nine of the thirteen hurricanes under investigation passed within 250 mi of Bermuda and approached the island from a southerly direction. In five of these cases, six- to 7.5-sec periods were generated on the approach of the storm, whereas, other storms and nearly all frontal systems generated four- to five-second periods. Of the 13 hurricanes, the periods after the storm had passed were four to five seconds in every case except one. The exception was that shown in Figure 3c.

Related wind, period, and ocean depth data will now be examined.

October 20, 1947 (Fig. 3a)--Very little wind information is available except that winds at Bermuda exceeded 100 mi/hr. Microseisms of 7.5 sec and shorter periods were recorded at the time of power failure.

August 26 - September 1, 1948 (Fig. 6a)--One hundred-knot winds were reported by air reconnaissance on August 28 and 30 and slightly less wind speed ten miles from the center on August 29 and 31. Microseismic periods were 5.5 sec through the duration of this storm.

September 11 - 15, 1948 (Fig. 3b)--Air reconnaissance reported 120-knot winds on September 12. Microseisms of 6.5 sec were recorded on this and the following day when the power failed on Bermuda.

October 6 - 8, 1948 (Fig. 3c)--This hurricane moved rapidly oceanward after it left Florida. Wind information at this time is not available except that the speed exceeded 100 mi/hr as it passed over Bermuda. Periods of five seconds were recorded before power failure and 7.5-sec periods were evident two days later after power had resumed.

September 3 - 8, 1949 (Fig. 3d)--The Weather Bureau reported that this storm reached great size and severity late September 7. The microseismic period was 6.5 sec.

August 15 - 21, 1950--In hurricane Abel (Fig. 6d), 120-knot winds were reported by aircraft August 17 and August 19. The microseismic period August 21 - 22 was 5.5 sec.

August 29 - September 5, 1950--In hurricane Charlie (Fig. 6d), 110-knot winds were reported August 30 at a time when six second microseisms were recorded at Bermuda.

August 31 - September 14, 1950--In hurricane Dog (Fig. 6d), the winds were reported by aircraft as unusually violent. Wind speeds on August 31 and September 3 were in excess of 125 knots and in excess of 100 knots from August 31 to September 9. Microseisms from September 3 to 10 were relatively large but the periods were normal. Until this point in this study, it appeared that wind violence had some part in controlling the microseismic period but evidence from this storm seems to negate that idea.

However, when Hurricane Dog was the most violent, it was 600 mi south of Bermuda when microseismic activity because of Hurricane Charlie was heavy, and if long period activity had originated from Hurricane Dog, it was too weak to show.

In regard to a relationship between ocean depths and microseismic period, there is likewise no conclusive evidence from this study.

British Admiralty and Hydrographic charts were examined critically with regard to position of the hurricane and microseismic periods. Of the area within 400 or 500 mi of Bermuda that to the southeast is slightly deeper than elsewhere in this area. A six-second period was attributed to Hurricane Charlie when it was in that area on August 29, 1950; but when Hurricane Fox was in the same area, six-second periods were not recognized from a routine search of the records. Furthermore, six- to 7.5-second periods were recorded when hurricanes were in other nearby areas, in two cases in the immediate area of Bermuda.

It appears therefore that period variations of storm microseisms at Bermuda are apparently independent of depth. A dependence on wind strengths, with perhaps a limiting factor governed by the depth of the ocean, has better support. If period does depend on wind strength [as was pointed out by KAMMER and DINGER 1951], it may be because the ocean swell period is also dependent on wind strength together with the expanse of ocean exposed to the wind, but that microseisms are generated only if the same period ocean swells are oppositely directed or have strong oppositely directed components. That may be one reason why wind strength-period dependence fails at times.

Conclusions

It has been demonstrated that 4.5-sec period microseisms at Bermuda large enough to rise above the normal background have local sources; six-second period microseisms may have local or or regional sources; and seven- to ten-second period microseisms may have local or distant sources. In every case, if the sources are from distances greater than a few hundred miles, the amplitudes are relatively small.

Fast-moving hurricanes approaching the island will not produce microseisms until the storm is on or close to the island, but if the forward motion of the hurricane is slow, the resulting ocean swell may reach the island first, in which case the strength of the microseisms probably depends on the strength and period of possible opposing swells, either from the wake of earlier hurricanes or from extratropical sources.

Heavy microseisms may be produced when no tropical or extratropical storms are in the area but when winds are favorable for the production of opposing swells.

The Longuet-Higgins theory of microseismic generation is supported.

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CALIBRATING SEISMOMETERS BY MEANS OF EARTHQUAKE DATA

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Abstract--Recordings of earthquakes were used to calculate the magnification of ground motion produced by various seismometers. The calculations were based upon the 'A' values (energy parameters) listed by Gutenberg for seismic waves P, PP, and S. Results of the calibration procedure indicate that the energy content of P, PP, and S waves recorded on Benioff instruments increases with increasing wave period. In order to calibrate the horizontal seismometers by use of recorded longitudinal waves, it is necessary to correct for the fact that the amplitudes recorded transverse to the direction of wave propagation are appreciable. The resultant calibrations were accurate enough to be used for a subsequent study of the energy content of seismic waves.

The energy content of seismic waves is commonly studied by ascertaining the ratio of the energy in the phase of interest to that of a phase whose energy characteristics are well known, such as P, PP, or S. For some phases, such as SKP, there is no phase suitable for an energy comparison. Hence, the energy content of such phases can be determined only by direct methods.

In order to analyze the energy content of a seismic wave directly, it is necessary to determine the magnifications used at the time the phase was recorded. Frequently, changes in the gain settings of the seismometers are not recorded, for the seismograms are used primarily for studies of travel times rather than energy. Consequently, the only way to determine the magnifications of such seismometers for any period in the past is to make use of their seismograms which have recorded phases whose energy characteristics are well known.

GUTENBERG [1945] has developed an equation for the calculation of earthquake magnitude from measurements of observed amplitude-to-period ratios of seismic body waves

$$M = A + \log|w/t| + K(M - 7) \qquad (1)$$

A = energy parameter calculated from travel data. A values are listed by GUTENBERG [1945] for different wave types as a function of epicentral distance
w = observed ground amplitude, microns
t = wave period, seconds
K = residual factor used to correct for the slight dependence of A values on magnitude

Substitution of W/R for w into (1), where W is the amplitude recorded on the seismogram and R is the magnification, and solving for R yields

$$\log R = A - M + \log|W/t| + K(M - 7) \qquad (2)$$

To account for the relative difference in ground sensitivity at various seismograph stations, the station ground factor, G, was added to (2)

$$\log R = A - M + \log|W/t| + K(M - 7) + G \qquad (3)$$

Eq. (3) was used to calculate the magnifications of several Pasadena and Huancayo seismometers. Amplitudes and periods were measured for earthquakes of magnitudes ranging from 7.0 to 7.7. The epicentral distance used for P ranged from 30 to 90°; that for PP, from 85 to 130°; and that for S, from 30 to 100°. Readings were not taken at epicentral distances where the A values listed by GUTENBERG [1945] changed abruptly. K was set equal to 0.2. G was set equal to 0.2 for Pasadena and to 0.0 for Huancayo. Earthquake magnitudes were taken from GUTENBERG and RICHTER [1949].

The ratios of the magnifications determined by earthquakes to the magnifications read from reference frequency response curves were computed. Markus Båth determined the absolute

Table 1--Sensitivity factors

Location	Type of instrument	Time interval tested		Number of observations
		from	to	
Pasadena	Short-period Benioff vertical	Apr. 1936	Feb. 1944	55
		Feb. 1944	July 1946	29
		Aug. 1946	July 1947	19
		July 1947	Jan. 1951	54
Pasadena	Long-period Benioff vertical	June 1938	Dec. 1950	62
Pasadena	Long-period Benioff N-S horizontal	Feb. 1937	Dec. 1950	46
Pasadena	Long-period Benioff E-W horizontal	Dec. 1937	Dec. 1950	46
Huancayo	Long-period Wenner N-S horizontal	Oct. 1932	Nov. 1942	48
Huancayo	Long-period Wenner E-W horizontal	Oct. 1932	Nov. 1942	44

magnifications of the short and the long-period, Benioff vertical seismometers at Pasadena in 1951. His values served as reference curves for all the short- and the long-period Benioff seismometers to be calibrated, both vertical and horizontal. For the Huancayo instruments, an arbitrary reference curve based upon the pendulum and galvanometer periods indicated by indicial response tests was used.

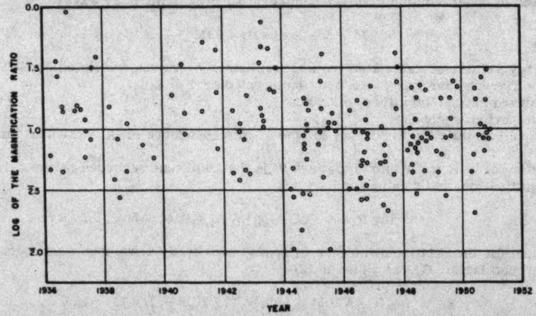

Fig. 1--Sensitivity of the short-period, vertical Benioff seismometer at Pasadena

The logarithms of the magnification ratios were plotted for each instrument on a separate graph. The log ratios were plotted against the dates of the earthquakes examined. Figure 1 shows such a plot for the short period, Benioff vertical instrument. The use of logarithms gives a statistically normal distribution of points. The very low values from 1944 to 1948 indicate that the sensitivity was definitely lower during that period.

The mean value of the log ratios was computed for each period during which the graphs indicated no change in sensitivity. The antilog of this value, designated as the 'sensitivity factor,' appears in Table 1, which lists some of the instruments calibrated.

The standard deviation of the log ratios from their arithmetic mean was generally about 0.3. This indicates that the standard deviation factor for the sensitivity (see Table 1) was about 2. For of various seismometers

Standard deviation factor	Pendulum period	Galvanometer period	Observed mean period	Sensitivity factor	Magnification at mean period
	sec	sec	sec		
2.3	0.99?	0.19?	1.38	0.43	4000 ± 25 pct
2.1	0.99?	0.19?	1.13	0.27	3500 ± 30 pct
1.8	0.99?	0.19?	1.33	0.20	2000 ± 30 pct
1.9	0.99?	0.19	1.32	0.33	3300[a] (± 20 pct)
2.0	0.99	1.12	3.36	0.97	910[a] (± 20 pct)
1.8	0.99?	0.95	3.18	0.97	960 ± 20 pct
2.2	0.99?	0.78	3.55	1.28	1140 ± 25 pct
2.0	8.5	11.8	6.25	0.89	900 ± 20 pct
2.0	9.3	12.8	6.27	1.00	1000 ± 25 pct

[a] Båth's value.

a standard deviation in the log ratio of 0.3, the Student's t distribution of statistics indicates that at least 30 log ratios must be averaged if there is to be 95 pct confidence that the true mean will not differ by more than 0.1 from the sample mean, or in other words, 30 readings are necessary to be 95 pct certain that the sensitivity is not in error by more than 25 pct. An abnormally high value for the standard deviation factor would suggest that the sensitivity had been changed during the time interval tested.

Since the sensitivity for the N-S component was suspected to differ appreciably from that of the E-W component for each pair of horizontal instruments, the components were calibrated separately.

Figure 2 shows that the log ratios increase with an increase of the azimuthal difference between the direction of wave propagation and the seismometer response axis. Hence, the procedure of dividing the amplitude of a P or a PP wave by the cosine of the azimuthal difference produces overcorrection. Figure 2 indicates that the energy recorded for P and PP is sizable even when the recording instrument is transverse to the direction of wave propagation. This may result from the fact that there is SH motion mixed with longitudinal motion or that appreciable energy has been horizontally refracted by lateral discontinuities in the Earth's crust.

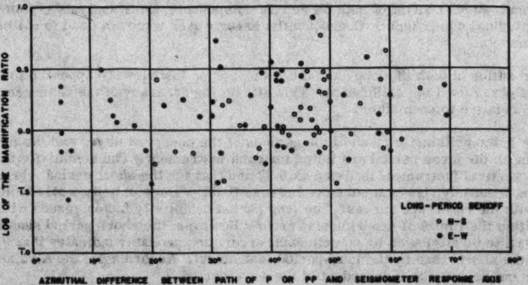

Fig. 2--Sensitivity of long-period horizontal Benioff seismometer

To eliminate such over-correction, the amplitudes were divided by a parabolic function, 1 - θ^2K, where θ equals the azimuthal difference, and K is a constant determined from the ratio of the square root of the energy appearing on an instrument oriented transverse to the direction of propagation to that appearing on an in-line instrument. Since there were only a few instances where a pair of horizontal instruments were so oriented, it was necessary to extrapolate the values for the recorded energy to what they would have been for such an orientation. The extrapolation is thus tantamount to a rotation of the horizontal instruments. In order to extrapolate, values for K were initially assumed, and subsequently refined by successive approximation. Energy values which required more than 30° of extrapolation were not used, for the ability to refine an assumed value for K is optimal when the horizontal components are transverse and in-line, and nil when they are oriented at angles of 45° with respect to the direction of wave propagation.

Since an energy ratio comparison for a pair of horizontal instruments depends upon the sensitivity of the instruments relative to each other, as well as K, the entire calibration procedure had to be repeated until the values determined for the sensitivity ratio and K remained stationary.

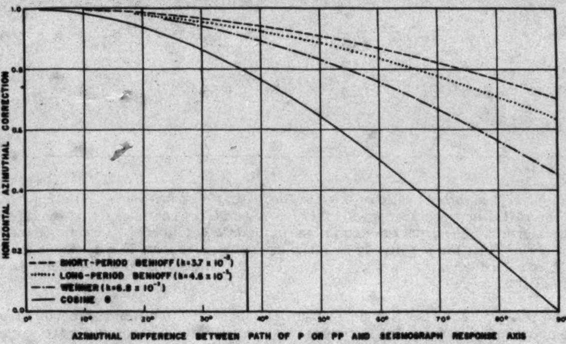

Fig. 3--Relation between azimuthal difference and horizontal azimuthal correction

In Figure 3, the upper three curves are a plot of the horizontal correction factor, 1 - θ^2K, where K serves as a parameter. Each curve indicates what the amplitude of a wave recorded as unity on the in-line component would be for various azimuthal differences. For θ = 90°, the short-period Benioff instrument has an amplitude equal to 0.8 that of its in-line value; the long-period Benioff, 0.63; and the very long-period Wenner, 0.45. This indicates that the longer the periods which determine the instrumental response, the 'purer' is the motion recorded for P and PP.

Since shear waves consist of both SH and SV components, their analysis is more complex than that for longitudinal components. Consequently, shear waves were not used to calibrate the horizontal instruments.

The gain ratios of both the long- and the short-period instruments appeared to be independent of the type of phase used for calibration. This attests the accuracy of the Gutenberg A values for P, PP, and S relative to each other.

In Table 1, the arithmetic mean of the periods of the observed waves and the magnification corresponding to the mean period are listed for each instrument. The sensitivity factor for the long-period, vertical instrument is listed as 0.97 and that for the short period, vertical instrument for the period from July, 1947, to January, 1951, as 0.33. Values of unity would indicate perfect agreement with the reference curves. The long period sensitivity factor agrees with a value of unity well within the limits of experimental error. However, the short-period sensitivity factor is much too small to be attributed to experimental error, and probably indicates that less energy was recorded by the short- than by the long-period instrument. Accordingly, the A values listed by Gutenberg do not seem to be independent of the wave period.

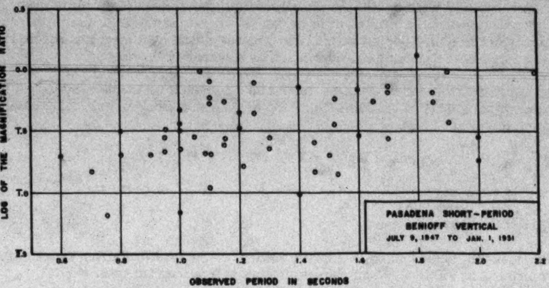

Fig. 4--Relation of magnification ratio to period of phase used

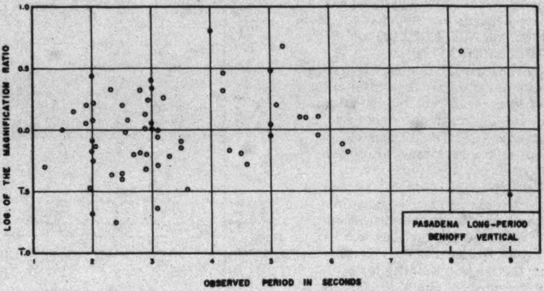

Fig. 5--Relation of magnification ratio to period of phase used

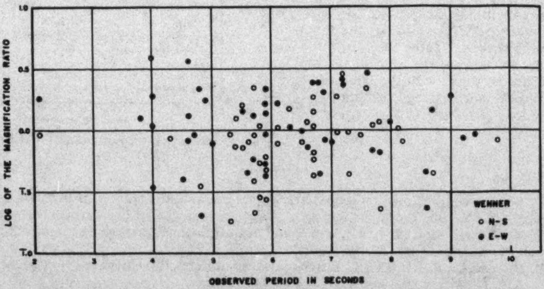

Fig. 6--Relation of magnification ratio to period of phase used

Figures 4, 5, and 6 show plots of the log of the magnification ratio versus the period of the phase used for calibration. The plots for the Benioff instruments indicate that the value of the log ratio increases with increasing period. The plot for the Wenner instruments is random. The plots suggest that the energy content of P, PP, and S increases with period except for waves of periods as long as those recorded on the Wenner instruments.

For the long-period instruments, the magnification of the mean period was determined by multiplying its value on the reference curve by the sensitivity factor. However, because the sensitivity factor of the short-period instrument was too small by a factor of three, the magnification obtained for this instrument was increased by a factor of three.

Complete magnification curves can be determined for each instrument by use of the magnification of the mean period listed in Table 1 and the response factor for critically damped electromagnetic seismometers:

$$\text{Response factor} = T/(1 + T^2/T_o^2)(1 + T^2/T_g^2) \quad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

T = period of wave motion
T_o = period of the pendulum
T_g = period of the galvanometer

Several causes can be advanced to explain the large standard deviation factors associated with the gain ratios listed in Table 1. Such causes are not independent of each other:

(1) A values are not independent of frequency.

(2) The basic assumptions upon which the magnitude scale depends are approximate empirical relations [see GUTENBERG and RICHTER, 1942; GUTENBERG, 1945].

(3) Energy emanates from the hypocenter of an earthquake asymmetrically with azimuth.

(4) Eq. (4) is derived for steady state solutions; hence, its application to short seismic pulses will introduce significant error.

(5) Sometimes the maximum amplitude within a phase does not signify maximum energy. In Figure 7, a slope of 45° to the right indicates that energy is constant for waves of constant amplitude, but different frequencies. The slope for the long-period Benioff instrument is close to 45°. Hence, the waves with the largest amplitudes will contain the most energy. The slope for the short-period Benioff instrument is much steeper than 45°. For waves of the same amplitude, those with the longer periods will contain more energy. The slope for the Huancayo instrument reverses from the left to the right as the period increases. For waves of the same amplitude, those with the shorter period will contain more energy, except for waves of very long periods.

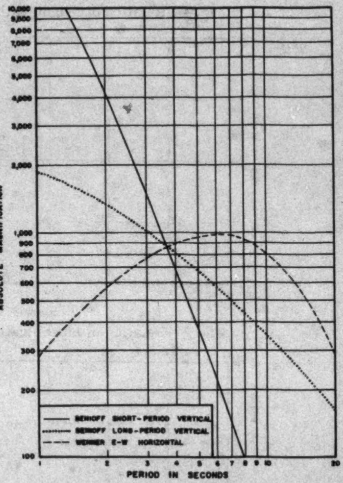

Fig. 7--Relationship of magnification and period

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THE RELATION BETWEEN MAGNITUDE AND ENERGY OF EARTHQUAKES

Markus Båth

Abstract--Relations between magnitude and energy of earthquakes given earlier are briefly reviewed. A new relation is derived using energy computations based on complete integrations of the Rayleigh wave phase. Twenty-seven shallow-focus earthquakes in 1952-1953 covering the magnitude range 5.3 - 7.8 recorded by the Galitzin instruments at Kiruna have been used. The resulting formula is $\log E = (7.2 \pm 0.5) + (2.0 \pm 0.07)\,M + \log (x/2)$, where the last correction term takes account of the ratio x of the total energy of the seismic waves and the energy of the Rayleigh waves.

Introduction--The magnitude scale of earthquakes was first defined by RICHTER [1935] by means of local records of shocks in Southern California. Later the application of this magnitude scale was extended in a series of papers by GUTENBERG [1945abc]. The importance of the magnitude definition lies in the fact that it assigns to every earthquake a number (the magnitude), which depends only upon the total energy of the seismic waves sent out by the earthquake. A knowledge of this energy is of essential importance in studies of the dynamics of the Earth. However, the relation between magnitude and energy has until now been only imperfectly known.

Some consideration of energies was given by RICHTER [1935]. The first relation between energy E and magnitude M was given by GUTENBERG and RICHTER [1936], that is

$$\log E = \log E_0 + 2\,M \quad \ldots\ldots\ldots\ldots \quad (1)$$

where $E_0 \simeq 10^8$ ergs. All logarithms in this paper are to the base 10. This formula was based on a variety of energy estimates of earthquakes. In connection with a study of intensities, accelerations of earthquakes GUTENBERG and RICHTER [1942] proposed the formula

$$\log E = 11.3 + 1.8\,M \quad \ldots\ldots\ldots\ldots \quad (2)$$

This was derived for shocks at the usual depth in California. GUTENBERG and RICHTER [1949] changed this formula to

$$\log E = 12 + 1.8\,M \quad \ldots\ldots\ldots\ldots \quad (3)$$

corresponding approximately to a four-fold increase of E. In deriving (2) only one kind of wave and only the kinetic energy were considered. There is approximately equal partition of energy between longitudinal and transverse waves, and the potential and kinetic energies are in the mean equal. This explains the four-fold increase of E in (3). The constant term may be in error by one unit or even more according to GUTENBERG and RICHTER [1949]. The formula (3) has been used by many authors. In 1951, Benioff, in a private communication, found from computations of the energy of the San Francisco earthquake of 1906 that the energy given by (3) was by far too large. BULLEN [1953] found that 'either this formula gives the energy of large earthquakes too great by a factor rather greater than ten, or that the fracture-resisting strength of the material in the focal region of the greatest deep earthquakes is at least of order 500 kg/cm^2.' Later GUTENBERG and RICHTER [1954] gave the formula

$$\log E = 11 + 1.6\,M \quad \ldots\ldots\ldots\ldots \quad (4)$$

which implies a considerable reduction of E compared with (3). This formula is, however, only tentative, and not the final answer. Later investigations by Gutenberg, Benioff, and Richter noted in private communications in 1954, have entailed considerable revision also of this formula.

The present author has derived a new relation between E and M from a large number of energy computations of earthquakes. These computations were based on amplitude and period measurements along the whole train of surface waves on records obtained on the Galitzin instruments at Kiruna.

Methods and materials used-- The method used is based on a complete energy computation of the whole train of Rayleigh waves, including the coda. Only the horizontal components need to be measured. The method is not new, but it has been very little used earlier. It was given by JEFFREYS [1923] and applied by him to a calculation of the energy of the Pamir earthquake on February 18, 1911. The formula I have used is

$$E_{LR} = 4\pi^3 \rho\, r_0 \sin\Delta\, e^{k\Delta} \int H c A^2 \tau^{-2}\, dt \ldots\ldots\ldots\ldots (5)$$

where ρ = the density of the ground
r_0 = the radius of the Earth
Δ = the epicentral distance
k = the extinction coefficient of the energy of Rayleigh waves
H = $1.1\,\lambda$, where λ = the wave length
c = the wave velocity
A = the horizontal amplitude
τ = the period
t = the time

The integration is extended over the whole Rayleigh wave phase. For derivation reference is made to BULLEN [1947, pp. 230-233]. The formula (5) differs from Bullen's formula in the factor $e^{k\Delta}$. The extinction factor was found to be of numerical importance for the surface waves and was therefore included. The deviations between the simple Rayleigh wave theory and the conditions in the actual earth are not so serious but that this method will give the correct order of the energy.

Every measurable crest and trough on the seismogram was measured (both with regard to period and amplitude) from the beginning of LR to the end. The coda waves certainly last a long time compared to the time occupied by the maximum motion, but due to the smaller amplitudes the coda contributes according to my measurements only three to ten per cent of the total energy of the surface waves. As we are only concerned with orders of magnitude of the energy in this investigation, the coda is no trouble. All measurements were made on the Galitzin records obtained at the seismograph station at Kiruna (67° 50.4′ N, 20° 25.0′ E). The constants of the instruments are well known, and during the time under investigation (1952-1953) determinations of the constants were made on January 7, 1952, December 27, 1952, and August 17, 1953.

The numerical integration was performed in the following way. We put

$$H = 1.1\,\lambda = 1.1\,c\tau$$

The integral becomes, putting c outside

$$\int (A^2/\tau)\, dt = \sum_i (A_i^2/\tau_i)\, \Delta t_i$$

Each time interval Δt_i is taken as the time between two successive zero-line crossings of the seismogram trace, that is, between two points 180° apart. During every such interval A and τ (amplitude and period) are supposed constant, and therefore the integral above can be replaced by the sum. Furthermore in every such interval $\Delta t_i/\tau_i = 0.5$ and therefore

$$\int (A^2/\tau)\, dt = 0.5 \sum_i A_i^2$$

It is to be noted that this is valid if both crests and troughs are measured.

The surface waves often show beats, probably due to interference between two or more wave trains. This circumstance is, however, of no essential consequence in this investigation [BÅTH, 1949, pp. 42-43].

In the numerical computations the following values were used: $\rho = 3.3$ g/cm^3, $r_0 = 6.37 \times 10^8$ cm, $k = 3 \times 10^{-4}$ km^{-1}, $c = 4.0 \times 10^5$ cm/sec. Our knowledge of the extinction of energy of the surface waves is rather incomplete. The value adopted here is a mean value obtained from GUTENBERG [1945a] and used by him in deriving the magnitude formula for surface waves.

The formula for E_{LR} given above supposes equal radiation of energy in all directions in the surface waves. This is, however, often very far from being true. For instance, in the California earthquake of July 21, 1952, there was much more energy of the surface waves emitted in the direction of Europe than in other directions. This circumstance has been eliminated in this investigation. The energies computed here under the assumption of equal radiation in all azimuths are compared with magnitudes M obtained only from the surface waves recorded at Kiruna. The magnitudes given here (Table 1) may therefore show some deviations from determinations at other stations or by means of other waves. What we have done is in fact a replacement of the actual shock by a fictitious shock having equal radiation of energy in all directions, and where the energy received at the distance of Kiruna is everywhere equal to that observed at Kiruna. This procedure is perfectly reliable for establishing a relation between energy and magnitude. If we should like to know the energy in the Rayleigh waves of the actual earthquake, we should instead need to measure the records at a number of stations in different directions from the epicenter. This would increase the heavy labor and computations many times, and the result would not be more reliable, but probably less reliable. In other words, I have compared the magnitude, obtained by the usual methods from a single wave in the surface wave phase, with the integration over the whole train of surface waves; and it is very essential that both these determinations are made from the same records.

We want to combine M with the total energy of the seismic waves, E_{tot}. Other forms of energy, as for example, frictional heat, developed by the earthquake do not enter into the present problem. The relation between E_{LR} and E_{tot}, $E_{tot} = x\ E_{LR}$, is an unsolved problem. In the results given in Table 1 and Figure 1 I have assumed $x = 2$ (only shallow earthquakes were used). But my final formula has been made flexible in the way that it can be used for any value of x, provided x is known. It is clear that x depends upon focal depth, but even for shallow earthquakes it certainly varies from case to case due to different crustal structures and earthquake mechanisms. A certain x-value can only be some sort of mean value for shallow earthquakes. My own measurements indicate that the energy of LQ amounts roughly to 1/4 - 1/2 of the energy of LR. The energy of P and S are approximately equal to each other [GUTENBERG 1945bc]. BULLEN [1947, p. 231] believes that for shallow shocks the greater part of the released energy goes into forming surface waves. JEFFREYS [1923] in calculating the energy of the Pamir earthquake in 1911says that 'the energy in the primary wave is not more than a few per cent of that in the secondary, which in its turn is only about five per cent of that in the long waves.' However, the total energy of especially the P waves is very difficult to measure due to their spectrum. It is not sufficient in the case of P to use only one instrument; in fact, a series of instruments with different periods covering the P-spectrum would be necessary. Another difficulty is the very rapid dissipation of the high-frequency motion already in the epicentral region. JEFFREYS [1952, p. 101] says that the whole energy of the earthquake is unlikely to be more than twice the energy of the surface waves. There is evidently room for more work on the partition of the energy on the different seismic waves.

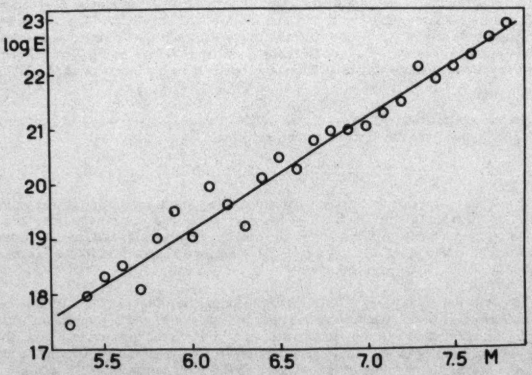

Fig. 1--Relation between log E and M; the circles are the observations, and the straight line represents the least-squares solution

Table 1--Earthquakes used in the energy computation

Date	Origin time GMT	Epicenter		Δ Kiruna	log E	M
		Lat.	Long.			
	h m s	°	°	°		
July 23, 1953	01 05 44	26 1/4 N	65 E	50	17.45	5.3
July 22, 1953	12 52 12	42 N	143 1/2 E	63	17.97	5.4
June 7, 1953	12 23 56	20 N	70 W	72	18.31	5.5
Apr. 6, 1953	03 49 32	9 3/4 N	123 3/4 E	87	18.52	5.6
Feb. 23, 1953	00 46 08	29 1/2 N	81 E	52	18.09	5.7
June 16, 1953	09 53 06	31 N	141 E	73	19.01	5.8
June 18, 1953	10 04 48	6 1/2 S	155 E	112	19.51	5.9
Oct. 13, 1953	08 53 45	30 N	113 1/2 W	78	19.04	6.0
Apr. 6, 1953	00 36 16	7 1/4 S	131 E	104	19.95	6.1
May 24, 1953	01 19 55	51 S	28 W	123	19.62	6.2
July 9, 1953	19 02 06	40 1/4 N	78 1/2 E	42	19.23	6.3
Aug. 25, 1953	02 04 16	4 1/4 S	152 3/4 E	108	20.09	6.4
May 31, 1953	19 58 35	20 N	70 1/2 W	71	20.46	6.5
Dec. 2, 1953	04 24 51	2 3/4 S	141 1/2 E	104	20.22	6.6
Apr. 30, 1953	06 26 40	20 1/2 S	170 E	129	20.76	6.7
Sep. 23, 1953	02 14 36	50 1/2 N	156 E	57	20.91	6.8
Dec. 25, 1953	01 51 29	53 N	159 3/4 E	56	20.96	6.9
Nov. 26, 1953	08 14 12	34 N	141 E	69	21.01	7.0
Jan. 13, 1952	04 03 37	22 N	124 1/2 E	75	21.25	7.1
May 19, 1952	18 32 21	42 1/4 N	143 1/2 E	63	21.46	7.2
Dec. 6, 1952	10 41 14	8 S	157 E	114	22.11	7.3
Dec. 12, 1953	17 31 23	3 3/4 S	80 3/4 W	98	21.88	7.4
July 21, 1952	11 52 14	35 N	119 W	73	22.12	7.5
May 6, 1953	17 16 48	36 1/2 S	73 W	124	22.32	7.6
Nov. 4, 1953	03 49 04	12 1/2 S	166 1/2 E	121	22.32	7.6
Mar.19, 1952	10 57 09	9 1/2 N	127 E	88	22.66	7.7
Apr.23, 1953	16 24 17	4 S	154 E	109	22.89	7.8

The 27 earthquakes measured are all listed in Table 1. The earthquakes used in this study were generally at greater distances due to the requirement of well-developed surface waves. The data on location and origin time have been obtained from USCGS or BCIS. The earthquakes measured cover the magnitude range 5.3 - 7.8. Outside these limits it was practically impossible to make the measurements required. E given in Table 1 as log E refers to E_{tot}, assuming $x = 2$, and M is determined from the surface waves at Kiruna according to the usual method [GUTENBERG, 1945a].

Results--The corresponding values of log E and M (Table 1) are plotted in Figure 1. The straight line in Figure 1 corresponds to the least-squares solution. Its equation is

$$\log E = (7.2 \pm 0.5) + (2.0 \pm 0.07) M \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

It is obvious that a linear equation is the best solution; there is no indication of curvature in the magnitude range 5.3 - 7.8 justifying any term of the second degree. Furthermore, it is clear that the same equation suits the whole interval used very well. And we may safely use it down to $M = 5.0$ and up to at least $M = 8.0$, possibly even up to $M = 8.6$, corresponding to the largest recorded earthquakes. For $M < 5.0$, however, there may be other formulae.

The standard deviation of log E is ± 0.27, corresponding to a factor of 1.9 in E. It is clear from Figure 1 that the scatter of the observations is much less above $M = 6.5$ than below this value. In addition to the casual error there is the systematic error due to the uncertainty of x, the ratio of the total energy and the energy of the Rayleigh waves. We have assumed $x = 2$, but if any other value of x is closer to the truth this changes only the value of the constant term (7.2), whereas the slope (2.0) and all error computations are unaffected. Therefore we can write our final formula in the following form

$$\log E = (7.2 \pm 0.5) + (2.0 \pm 0.07)\,M + \log x/2 \quad \ldots\ldots\ldots\ldots\ldots (7)$$

If future investigations will give some more reliable value of x for shallow-focus earthquakes, this can be put into this formula, and the result of our investigation is still valid. On the whole, it is evident that the slope of the line is much better determined than the constant term. Even if x should have a systematic variation with M for shallow-focus earthquakes, our equation (7) is valid.

Formulas (6) and (7) have been derived for shallow-focus earthquakes. For deep-focus earthquakes GUTENBERG [1945c] correctly developed the magnitude formula according to the principle that a given magnitude should always correspond to the same energy, irrespective of the focal depth. Therefore (6) is valid for earthquakes of any focal depth. The same applies to (7) when the correct shallow-focus value of x has been inserted.

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THERMAL EXPANSION OF SOLIDS AND THE TEMPERATURE AT THE BOUNDARY OF THE EARTH'S CORE

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Abstract--The empirical relation $\alpha T = b(T/\theta)^{1.5}$ where b is a constant and θ the Debye temperature, represents satisfactorily the variation with temperature T of the coefficient of thermal expansion α at ordinary pressure. The dimensionless constant b is found to have the same value $(24.7 \pm 4.5) \times 10^{-3}$ for a large number of substances, including oxides, silicates, and diamond. Limits can be set to the variation of b with pressure. Taking values of α and θ at the core's boundary from seismic data, and solving the above relation for T, it is found that the temperature at that depth is not likely to exceed 2700°K.

Notation--The following symbols are used:

ρ = density
V = molar volume
P = pressure
T = temperature
S = entropy
θ = Debye temperature
C_P, C_V = molar specific heat (cal/mole deg) at constant P, V, respectively
c_P, c_V = specific heat per gram
$K = -V(\partial P/\partial V)_T \quad K_s = -V(\partial P/\partial V)_s \quad \alpha = (1/V)(\partial V/\partial T)_P$
g = acceleration of gravity
r = distance from the Earth's center
$\phi = K/\rho \quad \phi_s = K_s/\rho$
$\epsilon = 1 - (1/g)\, d\phi_s/dr$
$\beta = -dT/dr \quad \tau = \beta - (\alpha T/\rho c_P)$
γ = Gruneisen's ratio $= \alpha C_V/KV = \alpha C_P/K_s V$
R = gas constant = 1.986 cal/mole deg
M = molecular weight
n = number of atoms in the chemical formula
m = mean atomic weight = M/n

Introduction--Because of its fundamental importance in geophysical problems, the temperature distribution in the Earth's mantle has attracted considerable attention in recent years. Attempts have been made to determine this temperature distribution from seismic data. The relevant information is condensed in an exact relation, applicable to a homogeneous medium, given by BIRCH [1952]

$$1 - \epsilon = (\partial K/\partial P)_T + A\,T\alpha\gamma + B(T\alpha\gamma)^2 + C\,\alpha\phi_s\tau/g \quad \text{. . . . . (1)}$$

which may be put in the form

$$1 - \epsilon = (\partial K/\partial P)_T + 2T\alpha\gamma\,[(\partial K/\partial P)_T + (1/\alpha K)(\partial K/\partial T)_P - 1] + (C\alpha\phi_s/g)\,\beta + O(T^2\alpha^2\gamma^2) \quad \text{. . (2)}$$

where A, B, and C are dimensionless quantities related to the parameters

$$(\partial K/\partial P)_T, \quad (1/\alpha K)(\partial K/\partial T)_P, \quad \gamma, \quad (1/\alpha^2)(\partial\alpha/\partial T)_P \text{ and } (1/\alpha C_P)(\partial C_P/\partial T)_P,$$

all of which are probably of the order of a few units, and the symbol O before the last parenthesis in (2) means 'a term of the order of.' As ϵ is known at all depths from seismic data, T and β could be found at any depth, given the value of either T or β at one depth and the exact numerical values of the parameters. We note, however, that α is of the order of 10^{-5} and T is probably much less than 10,000°; hence $T\alpha\gamma$ is of the order of 0.1 at most, and $\alpha\phi\beta/g$ is of the same order. The quantities ϵ and $(\partial K/\partial P)_T$, on the other hand, are about 3. $(\partial K/\partial P)_T$ and $(1/\alpha K)(\partial K/\partial T)_P$ usually have closely similar values, but of opposite sign, so that even the signs of C and of the coefficient of $T\alpha\gamma$ in (2) are not known with certainty. It follows, as noted by Birch, that (2) cannot yield more than an order of magnitude for T. To compute a more precise value of T one must introduce additional assumptions which commonly consist of choosing an approximate value for one or the other of the unknown coefficients. We briefly examine the validity of some of the approximations that have been suggested.

The approximation C_V = constant--An approximation that is commonly made (for example, MIKI, 1954) in calculations concerning the interior of the Earth is that the temperature is sufficiently high that C_V has reached its classical value 3nR; hence $(\partial C_V/\partial T)_P = (\partial C_V/\partial P)_T = 0$. It is easy to show that this approximation is not likely to be valid. From the relation

$$C_P - C_V = TV\alpha^2K \qquad (3)$$

and noting that

$$(\partial\alpha/\partial P)_T = (1/K^2)(\partial K/\partial T)_P \qquad (4)$$

we get by differentiation with respect to P at constant T,

$$(1/TV\alpha^2)(\partial C_V/\partial P)_T = -(\partial K/\partial P)_T - (2/\alpha K)(\partial K/\partial T)_P - (1/\alpha^2)(\partial\alpha/\partial T)_P \qquad (5)$$

To evaluate the term on the left, we note that for $T \geq \theta$, Debye's expression for the specific heat can be well represented by the simple function

$$C_V = 3nR[1 - (1/20)(\theta/T)^2] \qquad (6)$$

Assuming n = 7, as for olivine, we get $(\partial C_V/\partial P)_T = -2.1\ R(\theta/T^2)\ d\theta/dP$. If we adopt the estimate of BIRCH [1952] of θ, we have

at 1000 km depth $0 = 1060°$ $P = 0.39 \times 10^{12}$ dynes/cm²
at 2600 km depth $0 = 1280°$ $P = 1.2 \times 10^{12}$

from which we obtain an average value for the deep mantle of $d\theta/dP = 2.75 \times 10^{-10}$. We also have $\alpha \approx 10^{-5}$, $V \approx 25$ cm³ for olivine. Hence, for $T \approx 3000°$ $(1/TV\alpha^2)(\partial C_V/\partial P)_T = -0.9$ which is certainly not negligible in comparison with $(\partial K/\partial P)_T$, γ, or $T\alpha\gamma$.

There are two reasons why the approximation C_V = constant breaks down. The first is that, according to (6), C_V still departs from its classical value by about two per cent at $T/\theta = 2$. Although the variation of C_V with pressure is admittedly small in this temperature range, we note from (5) that it is to be divided by $TV\alpha^2$, which is also very small, and the ratio of the two may still be appreciable, as shown. In addition, there are indications that C_V may never become independent of temperature because of anharmonic terms in the lattice vibrations. This may be illustrated by the case of olivine.

Specific heat of olivine--KOZU and TSURUMI [1934] have determined the thermal expansion, in the range 300-1300° K, of an olivine from St. John Island with $\rho = 3.3$ and which, from its chemical analysis, appears to contain about nine per cent fayalite.

The thermal expansion can be represented by the relation

$$\alpha = 1.73 \times 10^{-5} + 2 \times 10^{-8}\,T \qquad (300° < T < 1300°\ K)$$

BRIDGMAN [1948] has determined the compressibility of an olivine from the same locality and presumably of the same composition for which $K = 1.25 \times 10^6$ kg/cm² $= 1.225 \times 10^{12}$ dynes/cm² [VERHOOGEN, 1953]. BIRCH [1952] gives $K = 1.19 \times 10^{12}$ for forsterite and 1.04×10^{12} for fayalite.

ORR [1953] has determined the constant pressure specific heats of forsterite and fayalite as follows

forsterite Mg_2SiO_4 $C_P = 35.81 + 6.54 \times 10^{-3}\,T - 8.52 \times 10^5/T^2$

fayalite Fe_2SiO_4 $C_P = 36.51 + 9.36 \times 10^{-3}\,T - 6.70 \times 10^5/T^2$

Assuming that the specific heat varies linearly with the fayalite content, we get at 1300°K for an olivine with nine per cent Fe_2SiO_4

$$C_P = 44.2 \text{ cal/mole deg}$$

From Kozu's data we get $\alpha_{1300} = 4.33 \times 10^{-5}$ and $V_{1300}/V_{298} = 1.0331$. Let us now assume that C_V has reached its classical value 21 R = 41.7 cal/mole deg. Solving (3) for K_{1300} we get

$$K_{1300} = \frac{(44.2 - 41.7) \times 4.186 \times 10^7}{1.3 \times 10^3 \times 45.6 \times (4.33 \times 10^{-5})^2} = 1.2 \times 10^{12} \text{ dynes/cm}^2$$

Take now $K_{298} = 1.225 \times 10^{12}$, as above. The variation of K with temperature is not exactly known, but BIRCH [1952] gives $(1/\alpha K)(\partial K/\partial T)_P = -7$ for olivine, and an average value of about -4. Hence $K_{1300}/K_{298} \approx (V_{1300}/V_{298})^{-4}$ and K_{1300} should be about 1.08×10^{12}, much less than the value 1.2×10^{12} just found; the discrepancy would be worse if we used the value -7. This either means that K is relatively insensitive to temperature (or even increases with temperature, if we adopt Birch's values of K_{298}), or that C_V is greater than its classical value by about 0.3 cal/mole deg, and greater than the expected value at $\theta/T = 0.54$ by more than one cal/mole deg. (The Debye temperature at 1300°K is about 750°, see Table 1). Similar calculations cannot be carried out at higher temperatures as α is not known beyond 1300°K, but we note that C_P still increases rapidly, being 45.9 for forsterite at 1600°K and about 50 for fayalite at its melting point (1490°). Thus the disagreement probably becomes worse at higher temperature, and the assumption that C_V has exactly its classical value is not valid in the range $T/\theta = 2$ to 4, which is the range in which we are interested.

Table 1--Thermal expansion data for a few metals (room temperature)

Element	$\alpha \times 10^5$	$\alpha T \times 10^3$	T/θ	$b \times 10^3$	$(3 R\theta/m\phi) \times 10^3$
Li	16.8	50.4	0.77	73.3	77.7
Na	21.3	63.9	2.0	22.5	...
K	24.9	74.7	3.4	12.0	...
Cs	29.1	87.3	3.31	4.8	...
Cu	5.0	15.1	0.97	15.7	...
Be	3.9	11.7	0.38	67.6	45.2
Mg	8.1	24.3	1.30	26.8	...
Ca	8.4	25.2	1.47	15.8	...
Al	6.9	20.7	0.78	29.9	...
Si	1.2	3.6	0.51	9.9	14.5
Pb	8.7	26.1	3.55	3.9	...
W	1.3	3.9	0.98	4.0	2.4
Fe	3.6	10.8	0.74	16.9	10.0
Pt	2.7	8.1	1.37	4.0	2.2
Average	...	...	...	22.0	...

The approximation $(\partial K/\partial T)_V = 0$--VALLE [1952] has based some calculations on the assumption that the isothermal compressibility depends on volume only; that is, its derivatives at constant volume are zero. This again can be shown to lead to unlikely results. Assuming that Valle is correct we would have

$$0 = (\partial K/\partial T)_V = (\partial K/\partial T)_P + (\partial K/\partial P)_T (\partial P/\partial T)_V = (\partial K/\partial T)_P + \alpha K (\partial K/\partial P)_T$$

or

$$(1/\alpha K)(\partial K/\partial T)_P = -(\partial K/\partial P)_T \quad \ldots\ldots\ldots\ldots\ldots (7)$$

Using (4) this can be transformed to $(\partial \alpha K/\partial P)_T = 0$; and since $\alpha K = (\partial S/\partial V)_T$, $\alpha V = -(\partial S/\partial P)_T$, we get also

$$\alpha + V(\partial \alpha/\partial V)_T = 0 \quad \ldots\ldots\ldots\ldots\ldots (8)$$

But $(\partial\alpha/\partial V)_T = (\partial\alpha/\partial P)_T\,(\partial P/\partial V)_T = -(1/KV)\,(\partial K/\partial T)_P$, so that (8) becomes

$$(1/\alpha K)\,(\partial K/\partial T)_P = +1$$

and by (7)

$$(\partial K/\partial P)_T = -1$$

which is unlikely, as $(\partial K/\partial P)_T$ is generally positive and $(1/\alpha K)\,(\partial K/\partial T)_P$ is generally negative. The reason why Valle's assumption is generally incorrect is that the thermal pressure in the solid varies with temperature even at constant volume; its contribution to the incompressibility is therefore not constant. In the following an attempt will be made to determine the temperature at the core boundary by use of an empirical relation between thermal expansion and temperature.

Thermal expansion--It does not appear to have been previously noticed that the temperature dependence of thermal expansion can be adequately represented by the empirical relation

$$\alpha T = b(T/\theta)^{1.5} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(9)}$$

where θ is Debye's temperature for the solid at temperature T, and b is a dimensionless constant which has very similar values for a large number of substances. This is illustrated by Figure 1 and Table 2 in which are given the experimental values of αT for various solids at various temperatures, the value of θ, and that of $b = \alpha T/(T/\theta)^{1.5}$. In the last column the value of $3R\theta/m\phi$ (see below) is listed for comparison.

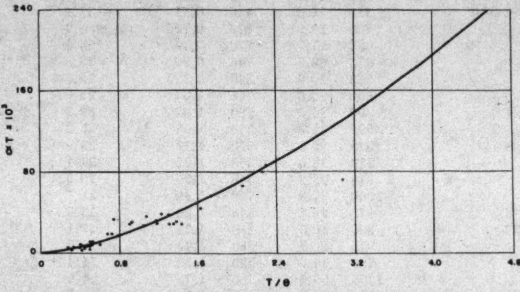

Fig. 1--Plot of αT versus T/θ for substances listed in Table I. The solid curve represents the function $\alpha T = 24.7 \times 10^{-3}\,(T/\theta)^{1.5}$

The Debye temperature entered in Table 2 is defined as the Debye temperature of the Debye solid that would have at a given temperature the same entropy per atom as the solid considered. For a few substances listed high-temperature entropies are not known; in such cases the value of θ at ordinary temperature has been used throughout. This approximation probably contributes to the scatter in value of b.

As a whole, the values of b computed in this way are remarkably uniform. A notable exception is that of quartz at 600° K, which reflects the abnormal rise in thermal expansion below the $\alpha\beta$ transformation point. As the thermal expansion of β-quartz above the transformation point is negative the average value of b over a wide temperature range would probably remain constant. Table 3 gives a comparison of values of b at different temperatures for those substances for which the temperature dependence of θ can be computed.

For the sake of comparison, values of b for a few metals at ordinary temperature are listed in Table 1. The average value of b is not very different from that for non-metals, but the scatter is considerably greater, which is undoubtedly due in part to the fact that the list only includes a few metals, some of which were selected precisely because of their abnormal properties. b now

Table 2--Thermal expansion data for non-metals[a]

Substance	Temp.	αT $\times 10^3$	θ	T/θ	$b = [\alpha T/(T/\theta)^{1.5}]$ $\times 10^3$	$3R\theta/m\phi$ $\times 10^3$
Diamond (C)	298	1.35	2140	0.14	26.0	32.5
Periclase (MgO)	200	4.8	745	0.27	34.6	. . .
Phenacite (Be_2SiO_4)	300	3.0	985	0.305	11.2	. . .
Corundum (Al_2O_3)	300	5.4	910	0.33	28.5	20.0
Jadeite ($NaAlSi_2O_6$)	293	5.8	745	0.385	24.4	24.5
Quartz (SiO_2)	300	8.2	750	0.40	32.2	66.3
Olivine (91 pct Mg_2SiO_4) (9 pct Fe_2SiO_4)	300	7.0	740	0.405	27.0	25.8
Zircon ($ZrSiO_4$)	300	2.7	740	0.405	10.5	23.0
Albite ($NaAlSi_3O_8$)	293	4.4	680	0.44	15.0	41.8
Rutile (TiO_2)	300	7.2	650	0.46	22.9	12.1
Nepheline ($NaAlSiO_4$)	293	9.2	615	0.475	28.2	41.0
Calcite ($CaCO_3$)	300	3.9	610	0.49	11.4	. . .
Hematite (Fe_2O_3)	300	6.9	610	0.49	20.0	14.8
Diamond	923	11.4	1865	0.495	32.5	. . .
Pyrite (FeS_2)	313	8.7	620	0.505	24.0	13.3
Corundum	473	11.4	910	0.52	30.4	. . .
Magnetite (Fe_3O_4)	314	8.2	530	0.59	18.0	10.8
Periclase	500	19.5	745	0.67	35.5	23.7
Fluorite (CaF_2)	313	18.8	440	0.71	31.4	17.2
Quartz	600	33.5	818	0.735	53.2	. . .
Olivine	600	17.6	770	0.78	25.5	. . .
Periclase	673	28.2	745	0.90	32.8	. . .
Pyrite	573	20.9	620	0.925	23.6	. . .
Olivine	800	26.6	770	1.04	25.0	. . .
Halite (NaCl)	300	36.0	280	1.07	32.7	19.5
Olivine	900	31.8	770	1.17	25.2	. . .
Corundum	1073	29.5	910	1.18	23.0	. . .
Fluorite	533	38.0	468	1.22	31.1	. . .
Jadeite	973	28.2	745	1.30	19.0	. . .
Olivine	1000	37.3	770	1.30	25.1	. . .
Calcite	873	20.8	645	1.35	13.3	. . .
Sylvite (KCl)	300	30.6	218	1.37	19.1	. . .
Albite	973	28.2	680	1.43	16.5	. . .
Magnetite	756	44.0	530	1.62	21.4	. . .
Olivine	1300	56.0	750	1.73	24.6	. . .
Fluorite	946	110.2	440	2.15	35.0	. . .
Halite	600	86.0	260	2.3	24.6	. . .
Halite	800	132.0	243	3.3	21.6	. . .
Halite	1000	201.0	230	4.35	22.2	. . .
Average	. . .	. . .	. . .	. . .	24.7 ±4.5 (P.E.)	24.8

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[a] Most values of α are from BIRCH, SCHAIRER and SPICER, Geol. Soc. Amer. Special Paper 36, 1942, and BIRCH, F., J. Geophys. Research, v. 57, pp. 227-286, 1952. Values for zircon, phenacite, hematite and quartz from MEGAW, M. D., Zs. Krist, v. 100, pp. 58-76, 1938. Diamond from KRISHNAN, R. S., Nature v. 154, p. 486, 1944. Fluorite (low temperature) and pyrite from PRESS, D. C., Proc. Indian Acad. Sci., v. 30A, pp. 284-294, 1949. Albite, nepheline, and jadeite from YODER, H. S., and WEIR, C. E., Amer. J. Sci., v. 249, pp. 683-694, 1951. Calcite from ROSENHOLTZ, J. L., and D. T. SMITH, Amer. Min., v. 34, pp. 846-854, 1949. Olivine with nine per cent fayalite from KOZU, S., VEDA, J., and TSUMURI, S., Proc. Imp. Acad., Japan, v. 10, pp. 83-86, 1934. Magnetite and fluorite (high temperature) from SHARMA, S. S., Proc. Indian Acad. Sci., v. 31, pp. 261-274, 1950. All entropy data from KELLEY, K. K., U. S. Bureau of Mines, Bull. 476 and 477, 1949 and 1950.

Table 3--Comparison of values of b at different temperatures (temperatures in parenthesis, °K)[a]

Diamond	Periclase	Corundum	Olivine	Fluorite	NaCl	Calcite	Magnetite
26.0(298)	34.6(200)	28.5(300)	27.0(300)	31.4(313)	32.7(300)	11.4(300)	18.0(314)
32.5(923)	35.5(500)	30.4(473)	25.5(600)	31.1(533)	24.6(600)	13.3(873)	21.4(756)
. . . . .	32.8(673)	23.0(1073)	25.0(800)	35.0(946)	21.6(800)	. . . . .	. . . . .
. . . . .	. . . . .	. . . . .	25.1(1000)	. . . . .	22.2(1000)	. . . . .	. . . . .
. . . . .	. . . . .	. . . . .	24.6(1300)	. . . . .	. . . . .	. . . . .	. . . . .

[a] Excluding the 600° value for quartz, the probable error on the values of b listed in Table 2 is 4.5 10^{-3}. This means that for one out of two substances chosen at random the value of b will fall within the indicated limits (24.7 ± 4.5) 10^{-3}.

shows a notable dependence on position in the periodic table. It is interesting to note the very similar values of b for cesium (4.8) and tungsten (4.0), in spite of the fact that the ratio of their thermal expansion is about 22. The value for iron falls within the range for non-metals listed in Table 2, which includes materials with such diverse properties that it seems unlikely that it would not include also mantle-forming minerals.

A further check on the validity of (9) may be obtained in the following way. As b is by definition independent of T, differentiation of (9) at constant P yields

$$(3/\theta)\, d\theta/dT = (1/T) - (2/\alpha)\, \partial\alpha/\partial T \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (10)$$

from which $d\theta/dT$ may be calculated if α and $\partial\alpha/\partial T$ are known; $d\theta/dT$ may than be compared with values determined from high-temperature entropy data. For an olivine with nine per cent fayalite we find:

at 300°K $\alpha = 2.33 \times 10^{-5}$ $\partial\alpha/\partial T = 2 \times 10^{-8}$ $\theta = 740$ $d\theta/dT = +0.4$
at 1300°K $\alpha = 4.33 \times 10^{-5}$ $\partial\alpha/\partial T = 2 \times 10^{-8}$ $\theta = 750$ $d\theta/dT = -0.04$

which we compare with experimental values of θ listed in Table 4.

Table 4--Debye temperature for fosterite and fayalite from entropy data

T	θ Forsterite	θ Fayalite
°K		
300	760	535
400	775	545
600	795	550
800	790	550
1,000	790	550
1,200	790	530
1,300	790	520
1,500	780	. .
1,700	765	. .

This comparison suggests that better agreement in the values of $d\theta/dT$ would be obtained by using a relation of the type

$$\alpha T = b' \, (T/\theta)^{1.4}$$

from which we would get $(d\theta/dT)_{300} = +0.15$, $(d\theta/dT)_{1300} = -0.08$, $d\theta/dT = 0$ for $T = 580°$. This slight change in the exponent of T/θ actually makes very little difference in our final result and does not seem to be well supported for some of the substances listed in Table 2.

A comparison of the last two columns in Tables 1 and 2 show that b is, on the average, rather close to $3R\theta/m\phi$. The relationship may, however, be accidental, at least at low temperatures. This may be shown in the following way. Assume $b = 3R\theta/m\phi$. Since we have also

$$\alpha = \gamma C_V/KV$$

substitution of $3R\theta/m\phi$ for b in (9) would give

$$\gamma = (3nR/C_V)\,(T/\theta)^{0.5} \quad . \; . \; . \; . \; . \; (11)$$

from which the value of γ can be found for any value of (T/θ). (Table 5)

Table 5--Gruneisen's ratio as a function of T/θ, according to (11)

T/θ	γ
0.2	1.21
0.3	0.90
0.5	0.86
1	1.06
2	1.43
3	1.74

Experimental values of γ for NaCl and MgO listed by BIRCH [1952] do not show any such temperature dependence, although the data are admittedly rather uncertain. Also, if $b = 3R\theta/m\phi$, we must have, since $(\partial b/\partial T)_P = 0$

$$(3/\alpha K)(\partial K/\partial T)_P + 1 = 1/\alpha T - (2/\alpha^2)(\partial \alpha/\partial T)_P$$

and since

$$(1/\alpha K)(\partial K/\partial T)_P = (1/\alpha K_s)(\partial K_s/\partial T)_P - \gamma$$

we get

$$(1/\alpha K_s)(\partial K_s/\partial T)_P = (1/3)[1/\alpha T - (2/\alpha^2)(\partial \alpha/\partial T)_P] + \gamma - 1 \quad \ldots\ldots (12)$$

For NaCl at 1000°K, $\alpha = 2.01 \times 10^{-4}$, $(1/\alpha)(\partial \alpha/\partial T)_P = 5.5$, and $\gamma = 1.5$, according to BIRCH [1952]; hence $(1/\alpha K_s)(\partial K_s/\partial T)_P = -1.5$ whereas the experimental value is -2.3. The agreement, which is good, breaks down completely at lower temperatures where $1/\alpha T$ is large. Thus the relation $b = 3R\theta/m\phi$ is probably only applicable at temperatures greater than 2θ or 3θ.

Dependence of b upon pressure--By differentiation of (9) with respect to P at constant T one gets, noting that $(V/\theta)(\partial\theta/\partial V)_T = -\gamma$

$$(K/b)\, db/dP = (1/\alpha K)(\partial K/\partial T)_P + (3/2)\gamma \quad \ldots\ldots\ldots\ldots (13)$$

Under normal conditions $(1/\alpha K)(\partial K/\partial T)_P$ is about -4, while γ is 1 to 1.5, so that $-(K/b)\, db/dP$ is 2.5 or less. At high temperature and ordinary pressure the numerical value of $(1/\alpha K)(\partial K/\partial T)_P$ probably decreases while γ increases, so that $-(K/b)\, db/dP$ would decrease or even change sign. The effect of pressure on $(1/\alpha K)(\partial K/\partial T)_P$ is not known, but JACOBS [1953] has noted that the thermal expansion in the deep mantle is given by the relation

$$\alpha = 1/(c_1 + c_2 P) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

where $c_1 = 2.78 \times 10^4$ deg and $c_2 = 5.45 \times 10^{-8}$ deg cm²/dyne. If β is the gradient in the deeper mantle along which (14) expresses the dependence of α on P, one obtains by differentiation of (14).

$$(1/\alpha K)\, \partial K/\partial T = -C_2 \alpha K - (\phi\beta/g\alpha)\, \partial\alpha/\partial T \approx -3.25 \text{ for } \alpha = 10^{-5}, K \approx 6 \times 10^{12} \text{ and}$$

neglecting the last term which is not likely to be more than 0.1 or 0.2. Since γ is close to 1, $-(K/b)\, db/dP \approx 1.75$ in the deeper mantle, showing that the value of this coefficient is not likely to vary much. Its average value in the mantle is also not likely to exceed the initial value 2.5.

Maximum temperature at the bottom of the mantle--Since the values of α and θ at the bottom of the mantle are known from seismic data, it should be possible to solve (9) for T at any depth if b were known at that depth. Our meager knowledge of the variation of $(1/\alpha K)(\partial K/\partial T)_P$ with depth does not allow, however, to use (13).

We may attempt to determine b from the relation $b = 3R\theta/m\phi$ which, as noted above, may be applicable at high temperature. The quantity $\phi_s = \phi\,(1 + T\alpha\gamma)$ is known from seismic data. The Debye temperature, also determined from seismic data, is about 1.28×10^3 at 2600 Km depth according to BIRCH [1952], and 1.25×10^3 at 2900 km depth, according to UFFEN [1952a]; we shall take the value $1\ 3 \times 10^3$ at the latter depth. The coefficient of thermal expansion α is 0.9×10^{-5} according to UFFEN [1952b], between 0.8 and 1.1×10^{-5}, according to BIRCH [1952], while VERHOOGEN [1952] gives $\alpha/c_P = 0.8 \times 10^{-12}$ sec² cm⁻²; we adopt here the value $\alpha = 1 \times 10^{-5}$ $\phi_s = 1.15 \times 10^{12}$ cm²/sec from seismic data, and as $T\alpha\gamma \approx 0.03 - 0.05$, we first neglect the difference $\phi_s - \phi$. m is probably close to 25 (m is 20 for forsterite, 29 for fayalite, 56 for iron). Then $b = 11.3 \times 10^{-3}$ and $T = 1740°K$. As this is much less than 2θ, the relation $b = 3R\theta/m\phi$ is probably not applicable, and the result may be discarded.

Since, however, we are mainly interested in setting an upper limit to the temperature at the core boundary, we can use (13) to find a lower limit for b. It has been shown that the maximum numerical value of $-(K/b)\, db/dP$ is about 2.5 so that the minimum value of b to be expected at the pressure P_1 prevailing at the bottom of the mantle is

$$b = b_o \exp\left(-2.5 \int_o^{P_1} dP/K\right)$$

with

$$b_o = (24.7 \pm 4.5)\ 10^{-3}$$

Now

$$\int_o^{P_1} dP/K = \ln(\rho/\rho_o)$$

where ρ is the density at the bottom of the mantle (5.6 gr/cm^2) while ρ_o is the uncompressed density of this material at the same temperature. This can hardly be less than 3.7 which is the minimum density of a homogeneous material consistent with the known variation of density with depth and the known moment of inertia of the mantle. BIRCH [1952] in fact gives $\rho/\rho_o = 1.4$ at most. Hence

$$b > b_o \exp[-2.5 \ln(5.6/3.7)]$$

or

$$b > (9 \pm 1.7)\ 10^{-3}$$

Hence, the maximum temperature T_m at the core boundary would be

$$T_m = (\alpha^2 \theta^3/b^2) = 10^{-10}(1.3 \times 10^3)^3/(81 \pm 2.4)\ 10^{-6} = 2700 \pm 100°K$$

the stated probable error being solely that arising from b_o. The significance of this probable error is that there would be a 50 pct probability for the maximum temperature to fall within the indicated range if nothing were known of the composition of the mantle. This probability is, of course, much greater if it is assumed that the mantle consists dominantly of olivine, since the value of b_o for olivine is known. The result is, as mentioned before, hardly affected by replacing the exponent of T/θ in (9) by 1.4, a value which seems to fit olivine slightly better than 1.5. However, allowance should be made for the uncertainty on α and θ, which cannot be estimated very closely. The error on α is probably of the order of ten or 20 pct, but as we have adopted a value of α somewhat larger than those given by Uffen and Birch, T_m is not likely to be much affected. The uncertainty on θ arises partly from our ignorance of the exact values of m and ρ, and also from the fact that Debye temperatures determined from elastic data may differ from the values obtained from specific heat or entropy data. Because of the strong dependence of T_m on θ, an error of 100° on θ could change T_m be several hundred degrees.

The value of T_m found here is in good agreement with the value 2500°C obtained by the author [VERHOOGEN, 1954] on the assumption that the maximum observed surface temperature of lavas reflects the maximum temperature in the mantle, corrected for adiabatic expansion and latent heat of melting. The value given here is also about one half of the probable melting point at that depth [UFFEN, 1952a, VERHOOGEN, 1954]. This suggests either that the mantle never was molten, or that the thermal conductivity in the lower mantle is considerably higher than the usually accepted value [UFFEN, 1952b], or that heat transfer occurs by some process considerably faster than conduction.

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RADIOGENIC SR^{87} IN MICAS FROM GRANITES

L. T. Aldrich, L. F. Herzog, W. H. Pinson, Jr., and G. L. Davis

Abstract--Additional samples of mica have been analyzed for radiogenic Sr^{87} by the method of isotope dilution. The proportion of radiogenic Sr^{87} in the Sr in each of these micas is much greater than that found previously. Three biotite samples have been reanalyzed using improved procedures, and in every case, greater proportions of radiogenic Sr^{87} were also found. As a result, biotite appears to be much more favorable as a mineral to be used for Rb-Sr age measurements. Since the source and isotopic composition of the Sr contamination in the earlier group of samples are not known, the Sr^{86}/Sr^{88} isotope variations reported by us at that time are of questionable value.

A study of radiogenic Sr^{87} in micas from granites was presented in this journal [HERZOG and Others]. In this work the promise of biotite for use in determining the age of the mineral by the Rb-Sr decay was demonstrated. Analyses of micas of three of the same granites used in the early study and of five additional granites have been made. It is the purpose of this note to report that the fraction of radiogenic Sr^{87} in the Sr found in mica is higher than that found before. In the earlier work Sr concentrates were obtained from mica concentrates containing zero to five per cent impurity minerals by standard chemical techniques. Additional purification of the Sr (to remove traces of Rb) was effected by ion exchange. They were then analyzed for radiogenic Sr by the mass spectrometer.

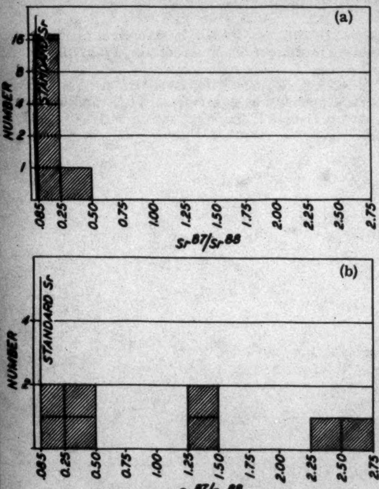

Fig. 1--Distribution of Sr^{87}/Sr^{88} ratios of biotites (a) reported in 1953, (b) in recent work; note that the scale of the ordinate on (a) is compressed indicating the small percentage of ratios, Sr^{87}/Sr^{88}, in the early work greater than 0.25

Micas from eight granites have now been separated and analyzed by isotope dilution for radiogenic Sr^{87}. Figure 1a gives the results presented in the previous work [HERZOG and Others, 1953] for micas. Figure 1b shows those for the recent work. It should be noted that the scale on the ordinate of the former is expanded. One reason the abscissa scale has had to be extended so far is that the main emphasis in the work at the Carnegie Institution has been on Precambrian rocks.

Three of the identical samples from the earlier work have been reanalyzed at the Massachusetts Institute of Technology. In two cases where an appreciable enrichment was found before, the ratio radiogenic Sr/normal Sr is slightly greater than reported previously. For the third sample, which is much lower in total Sr, a much higher proportion of radiogenic Sr was found in the second run. The results of the two sets of analyses are given in Table 1, together with the analyses of five biotites not previously analyzed. Radiogenic Sr in the sample from Calais, Maine is very low because it is Paleozoic, and has an abnormally low Rb content, only about 1/20 of the content of average biotite. It is apparent that the samples previously analyzed contained Sr of normal isotope abundance that was not a part of the biotite. Whether this Sr was contamination introduced in the chemical processing, or Sr in other minerals included in the biotite samples is not known.

Table 1--Comparison of results; Ratio Sr^{87}/Sr^{88} in Biotites

(Sr^{88} = 0.8256 total Sr of normal isotope composition and 87/88 for such Sr = .0850)

Locality		87/88	
	DTM (1951)	MIT (1954-55)	DTM (1953-55)
Stone Mtn., Ga.	0.2629	0.289	...
Hadderspell, Ont.	0.1714	0.183	...
So. Rhodesia	0.0942	0.433	...
Calais, Maine	...	0.088	...
Quartz Creek, Colo.	...	...	1.39
Capetown, S. Africa	...	...	1.38
Bagdad, Ariz.	...	...	2.41
Uncompahgre, Colo.	...	...	2.55

As a result of these new measurements it may be concluded that: (1) biotite is more suitable as a mineral for mineral age measurements than had been previously thought; and (2) since the source of contamination of the Sr in biotites reported earlier is unknown, the variation in the ratio Sr^{86}/Sr^{88} reported [ALDRICH and Others, 1953] for biotite is of unknown origin.

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THE DISCOVERY INVESTIGATIONS IN THE SOUTHERN OCEAN

G. E. R. Deacon

Abstract--The primary object of the investigations was to provide a scientific basis for the regulation of the whaling industry, and it included the pursuit of enquiries into the ecology, distribution and fluctuations of the plankton organisms which provide the whales with food. Most of the oceanographic survey has been done by the RRS Discovery II which was specially built for the purpose and by the RRS William Scoresby designed for whale-marking and fishery work. Fourteen expeditions have been sent to the Antarctic Ocean over a period of 27 years, and unique experience and comprehensive results have been obtained. The physical and chemical data have been published in the Discovery Reports and increasing use is being made of them. The investigations are being continued under N. A. Macintosh ar the National Institute of Oceanography.

The work of the Discovery Committee was concerned with the biology of whales and their oceanic environment mainly with a view to the proper regulation of the Antarctic whaling industry, but it was organized on very broad lines, and comprised the study of the hydrography and natural history of the whole of the Antarctic Ocean. The work was financed from a substantial Research and Development Fund built up by the Government of the Falkland Islands from taxes on whale oil processed in the Dependencies. Scott's former ship the Discovery was purchased and fitted for oceanographic work, and Stanley Kemp was appointed Director of Research. Kemp resigned in 1936, when he went to the Plymouth laboratory, and N. A. Mackintosh took his place. In 1949 the Discovery Committee was dissolved and its work taken over by the National Oceanographic Council.

The Royal Research Ship Discovery sailed in 1924, but she proved unsuitable for intensive oceanographic surveys, and was replaced in 1929 by the RRS Discovery II, specially designed for the work. The comparatively high speed and large bunker capacity of this vessel allowed the time to be used to much better advantage and the programs were put through far more expeditiously than before. Her longest Antarctic cruise from one refuelling point to another was 6300 mi, and her longest time at sea before refuelling 56 days. Figure 1 shows roughly the routes she has followed though it is not a complete or accurate record. She is 234 ft long, with a registered tonnage of 1063, and steam-propelled with a reciprocating engine. Her maximum speed is 13.5 knots and economical speed about nine knots; after 25 years she still does about 200 mi/day on about eight tons of oil. She has a main winch with 5000 fm of tapered steel wire and 1200 fm of trawl warp. Two hydrographic reels, each with 3500 fm of four-mm wire and a smaller reel with 700 fm are mounted on deck along the port side, separately driven by steam engines. The electric bathythermograph winch is right aft on the port side, and just recently a new steam winch for electric cable has been mounted on the starboard side forward. These machines have been an unqualified success.

Not counting her war services the RRS Discovery II has steamed some 500,000 mi, much of it in the stormiest seas in the world, and she has pushed through hundreds of miles of heavy pack-ice. She has always gone unaccompanied and was generally away from the United Kingdom about 20 months at a time. She made five such voyages before the War, under the Discovery Committee, and one since, under the National Oceanographic Council. Two of these included circumpolar voyages up to high latitudes in winter. During the Antarctic voyages she carried four deck officers in addition to the Master, three engineers, a surgeon, three to five scientists, one to three assistants and a crew of about 38. The Master and officers were appointed by the Committee or Council and the crew signed on under Merchant Service regulations.

On 'station' the ship was held very nearly head to wind, with the engines doing the least number of revolutions that would prevent her falling off to starboard. All the wires were lowered on the port side, and it was generally safe to work simultaneously deep bottles from the forward engine, nets from the after reel, and insulating water bottle (down to 400 m) amidships. It is most remarkable that the three wires could be used at the same time, but accidents were remarkably rare. With moderate or strong winds, an experienced officer on the bridge, and practised scientists at the

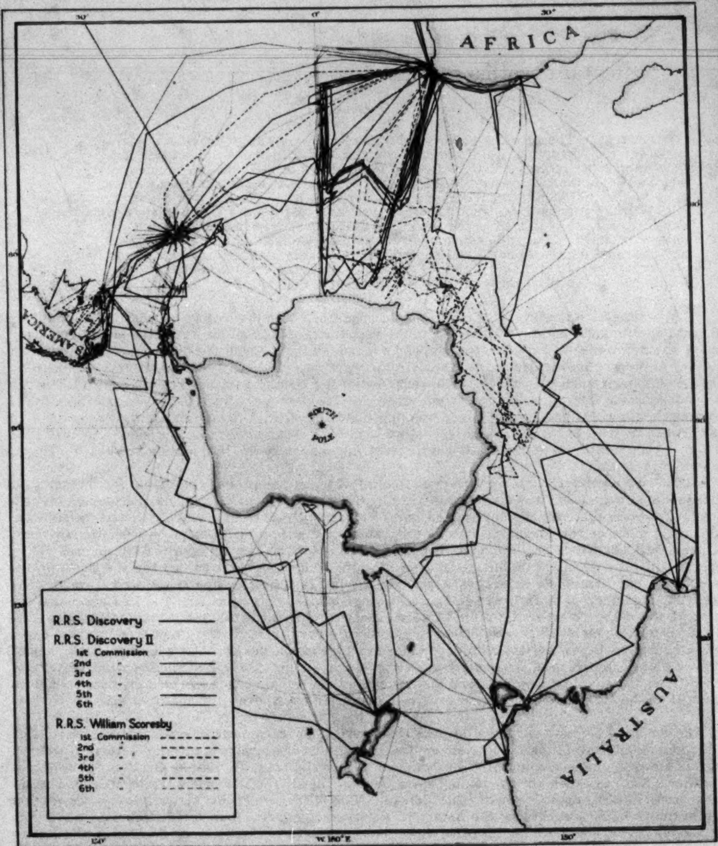
30°
0°
30°
AFRICA
S. AMERICA
SOUTH POLE
AUSTRALIA
R.R.S. Discovery
R.R.S. Discovery II
1st Commission
2nd
3rd
4th
5th
6th
R.R.S. William Scoresby
1st Commission
2nd
3rd
4th
5th
6th
150°
W 180° E
150°

Fig. 1--Principal voyage of the Discovery Committee's vessels, 1926-1939 and those, of the National Institute of Oceanography, 1950-1951

machines, the work went on month after month in almost any weather without loss or damage. If the ship started to fall off a short burst of full speed with the helm hard over brought her back without upsetting the wires. The wire angles were only a small fraction of what they would be with the ship lying to, and the worst angles and greatest risk of crossing the wires occurred when the wind was very light (less than eight to nine knots) so that the ship could not be held into it.

At a typical station samples were taken every ten meters down to 60 m and then at 80, 100, 150, 200, 300, 400, 600, 800, 1000 and every 500 m to the bottom. The deepest observation was from 7250 m in the South Sandwich Trench, and most stations went to 4500 m. Closing vertical nets were hauled from 1000 to 750, 750 to 500, 500 to 250, 250 to 100, 100 to 50, and 50 to 0 m; another haul with a fine net for phytoplankton was made from 100 to 0 m; and during the second half of the work there was usually a haul from 1500 to 1000 m and sometimes deeper. When the vertical lowerings were completed larger nets were towed obliquely with the ship doing two to three knots, from 250 to 100 m and from 100 to 0 m. The whole station, to about 4500m including the towed nets, usually took 4.5 hr and it was generally done at night when the ship often had to reduce speed because of ice. During long ocean voyages a station was worked every night, and all the chemical determinations, for salinity, oxygen content, phosphate, silicate, pH, and sometimes nitrate and nitrite, were made next day; the same bottles, procedure, and techniques were used day after day. The net hauls were dealt with as far as time would allow, and usually one or two species were picked out, counted and measured. The ship always had deep and shallow (navigational) echo-sounding, and sounding watches were kept.

The physical and chemical data, and details of net hauls are published in Station Lists in the Discovery Reports. So far, including the work of the smaller vessel RRS William Scoresby (see below), there are nine, and that for 1949-51 is just about to be printed. The Antarctic Ocean is in fact so well covered with temperature, salinity, and chemical data that future observations of the same kind are not likely to add much to what is known, unless they are on a much more intensive scale. The qualitative picture we have at present can be extended here and there, but no great advances are likely without an intensive program of current measurements in the subsurface and deep layers, and a more precise understanding of the relative importance of wind-driven and thermodynamic circulation. The qualitative picture, now some 20 years old, seems to hang well together however it is approached. A recent example is the paper by KOOPMAN [1953], which shows a close correspondence between the oceanographic boundaries and meteorological features, and between the silicate content of the surface water and the indication of convergence and divergence given by meteorological data.

The results of the work appear in the Discovery Reports of which 27 volumes have been published up to date. These reports are mostly on biological subjects. They contain much information on the the bionomics of whales and on the oceanic plankton, and many of them are systematic reports which have added considerably to what is known of the distribution of the marine faunas. Although the results already include much factual information and a number of useful generalizations there is little doubt that some of the most exciting work on the relation between animal distribution and the physical and biological environments remains to be done. The material already collected is very extensive and has the special advantage that it covers all parts of a major oceanic area at all seasons of the year. It seems sufficient to give a realistic basic picture and to test many hypotheses. Indeed it is an almost inexhaustible mine of material for interesting researches on particular species. Not all such work is of equal value but it seems best to press on with the more promising investigations before collecting fresh data. Good progress now will allow more profitable work in the field to be done in the future.

In 1926 the Discovery Committee built a second research ship the RRS William Scoresby, 134 ft long with a registered tonnage of 324. She made eight unaccompanied voyages to the Antarctic, and one to the South Indian Ocean. Six of the Antarctic voyages are shown in Figure 1; the seventh was to the Falkland Dependencies, and the eighth on war service in the same region. She has done much oceanographic work. She could not be held head to wind like the Discovery II, and however bad the weather, all the work had to be done beam on to the sea. As much of the chemical analysis as possible was done on shore. She was heavily engined for her size, and the difficulties and cost of modernizing her to meet Lloyd's and Ministry of Transport requirements, and of securing crews, have been largely responsible for the final decision to dispose of her last year.

As well as being concerned with whaling and oceanographic research, both ships have made extensive surveys which appear on Admiralty charts and the Admiralty's Antarctic Pilot.

Detailed accounts of both vessels, and of the objects of the work, including the equipment used, are given in the Discovery Reports. The unusual length and continuity of the work has afforded unique experience. H. F. P. Herdman, who has been very much concerned with the fitting out and equipment of the vessels since before they were launched, is, for example, writing an account of the behavior of the deep-sea thermometers, some of which have been used for more than 25 years.

Discovery II is now mainly engaged in new kinds of research in the North Atlantic Ocean. The marine physics has mainly to do with studies of waves and currents, particularly the development of methods of obtaining continuous records of deep-water movements. The marine biology has some emphasis on new methods of studying productivity and of catching the active deep-sea animals which escape towed nets. She is also being used for studies of the ocean floor. Till more development, analysis and theoretical work has been done the staff of the National Institute of Oceanography is not sufficient to keep her employed on first-class projects so that facilities are frequently afforded to other laboratories. Her latest task is to take a turn of duty as a weather ship on Station Kilo. She is operated for the National Oceanographic Council by the Royal Fleet Auxiliary, and all the officers belong to the service of that authority. This arrangement has proved very efficient and economical.

The possibility of a further voyage to the Antarctic after the International Geophysical Year is being considered.

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REVIEW OF THE OCEANOGRAPHIC PROGRAMS OF THE PACIFIC OCEANIC FISHERY INVESTIGATIONS

E. Dixon Stroup and Thomas S. Austin

Abstract--The Pacific Oceanic Fishery Investigations (POFI), U. S. Fish and Wildlife Service, has, since early 1950, been engaged in oceanographic surveys of the tropical and subtropical central Pacific, and since last year the northern temperate central Pacific. These studies support POFI's exploratory fishing program, stressing the location of areas of enrichment and increased productivity in the upper layers. The tabulated data from the cruises, together with vertical sections of the measured fields and brief descriptive texts, are published as Special Scientific Reports of the U. S. Fish and Wildlife Service. In the tropical central Pacific, standard oceanographic work is nearing completion, with reports published on seven cruises crossing and defining the equatorial current system (lat. 15°N-10°S, long. 140°W-180°). Similar reports on seven cruises in Hawaiian Islands offshore waters and three cruises to temperate waters north of Hawaii (lat. 25°N-40°N, long. 140°-170°E.) are in preparation. Plans for 1955 include a reconnaissance oceanographic cruise to the equatorial eastern Pacific in cooperation with Scripps Institution of Oceanography and the Peruvian Hydrographic Office, and participation in NORPAC, a joint survey of the entire Pacific north of 25°N. latitude during July, August, and September by POFI, SIO, the State of California, University of Washington, Pacific Oceanic Group of Canada, and Japanese agencies.

The Pacific Oceanic Fishery Investigations (POFI) of the U. S. Fish and Wildlife Service operates two boats equipped for offshore oceanographic surveys: the Hugh M. Smith, a 128-ft vessel of the west-coast tuna clipper design, and the Charles H. Gilbert, 112 ft, designed and built for oceanic fishery and oceanographic investigations. A third vessel, the 85-ft John R. Manning, is used exclusively in fishing surveys.

The POFI oceanographic programs supplement associated biological investigations; this has had important effects on the type of oceanographic studies made. Basically, observations at sea have been mostly limited to the upper 1000 m or less, with emphasis on processes occurring in the euphotic zone. Detailed investigations have been made of certain features of the circulation thought to be of importance biologically, to the exclusion of other features perhaps just as prominent from a physical viewpoint. In particular, close attention has been given to areas where the normal stability of the upper layers is in any way disturbed. This stability, very highly developed in the equatorial region, greatly restricts the replenishment of nutrients in the surface layer from below; any situation allowing this replenishment may be of extreme importance to the productivity of the region. As reviewed by SETTE [in press], locations where these conditions may occur include areas of surface divergence and upwelling, areas affected by the presence of islands, and areas of intensive mixing due to great horizontal or vertical shear (such as current boundaries and eddies); each of these has received close attention in the investigations. The measurements made - besides those essential to a basic understanding of the circulation - have been of the fields of such dissolved substances as phosphate and oxygen, which are of immediate and relatively obvious significance biologically. Quantitative zooplankton collections were made to provide a biological index of the productivity.

In order to get the oceanographic data as rapidly as possible into the hands of those who will use it, most reports so far published include only brief descriptions of methods and salient features, tabulated observed and interpolated data, plots, and vertical sections. These publications, Special Scientific Reports of the Fish and Wildlife Service, can be obtained on request from the POFI office in Honolulu. A few reports have appeared elsewhere; a list of all publications dealing with POFI oceanographic cruises is given at the end of this paper. A complete POFI bibliography and a comprehensive review of all oceanographic and biological results to 1954 are also available [SETTE, 1954].

Progress in oceanographic studies--The two areas in which POFI began surveys were the Hawaiian offshore waters and the tropical central Pacific. The first of these is the location of a commercial tuna fishery of a highly seasonal nature; it was hoped to gain greater understanding of the seasonal variations in these waters, and perhaps relate variations in catch directly to certain of these changes. While there was no fishery in the equatorial central Pacific, there were indications of upwelling and enrichment in connection with the equatorial currents, with consequent possibilities of increased productivity. In 1954 POFI started an oceanographic survey program in the temperate central Pacific north of Hawaii in connection with an investigation of the abundance of albacore in this area. While each of these regions is huge, many of the processes occurring in them can only be fully understood in the light of the entire Pacific oceanic circulation; in this connection an increasing effort is being made to coordinate POFI areas and cruises with those of other agencies investigating the Pacific.

Prior to POFI, cruises of the Challenger, the Carnegie, the Albatross, and, somewhat farther west, those of Operation Crossroads had made oceanographic observations in the tropical central Pacific. The location of the POFI station lines is shown in Figure 1. After reconnaissance cruises interest was centered on the area within 10° or 15° of the Equator, between 140°W and 180° longitude; a total of seven cruises (16 meridional sections) was made across the equatorial currents within these boundaries from 1950 to 1952. The first five of these were concerned with standard descriptive oceanography, whereas the last two were designed to give especially detailed information in the upper 500 m, one measuring the short-term variability in oceanographic features of the region and the other making direct observations of surface and deep currents. The data available for a description of the Pacific equatorial circulation are now much more complete than for the Atlantic.

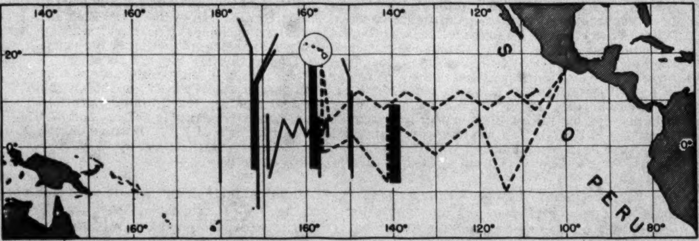


Fig. 1--Equatorial area; heavy solid lines indicate completed POFI oceanographic station lines; dashed line gives track of planned 1955 reconnaissance cruise during operation EASTROPIC; SIO and PERU indicate approximate areas of concurrent investigation by Scripps Institution of Oceanography and the Peruvian Hydrographic Office respectively

In general, the well-known pattern of the westerly North and South Equatorial Currents, separated by the return flow of the Equatorial Countercurrent at approximately 5° to 10°N., has been substantiated with detailed information regarding variability. In addition a second easterly current has been discovered which flows directly along the Equator beneath the westerly South Equatorial Current. The early ideas regarding meridional flow near the Equator have been corrected and amplified, including the confirmation of a single band of upwelling and mixing lying along the Equator. Under the influence of the trades this upwelling causes very significant enrichment of the surface layer immediately to the north and south. The pattern of enrichment is borne out strikingly in the biological studies of the area, but causes of variability of upwelling and enrichment are not yet well enough understood to explain all the observed changes in biological abundance.

No further standard oceanographic cruises are planned by POFI in the immediate future in this area. There may well be, however, cruises of a specialized nature, investigating imperfectly understood details of the circulation as they affect the productivity, and the reconnaissance cruise shown in Figure 1.

The primary analysis of the equatorial data is all but completed; only the report on the last completed cruise remains to be published. An over-all analysis of the data is now being undertaken, which will attempt to bring together the data from the various cruises into a detailed description of the region. Equatorial meteorology is being examined in an attempt to relate changes in upwelling and productivity to certain wind conditions. The relationships between the oceanography of this and adjoining regions are being closely examined.

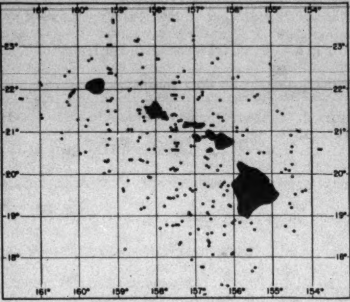


Fig. 2--Hawaiian Islands area; dots indicate positions of oceanographic stations completed

Oceanographic investigations in the Hawaiian Islands area were also very scanty before the POFI studies, consisting essentially of the ends of a few station lines extending between Hawaii and other points. The dense network of POFI stations occupied to the present is shown in Figure 2. The station pattern, relatively small at first, was expanded when the complexity of the island circulation became appreciated; it is still apparent that the islands affect the flow considerably beyond our area of detailed investigation. In a situation of this nature only the most general description can be drawn; it is very difficult to predict any specific oceanic event. The most notable features of the circulation that have come to light are large, semi-permanent counterclockwise eddies downstream from the Islands. The dynamics of these eddies are obscure, and there is no definite evidence of the eddies affecting the productivity of island waters.

Reports covering the seven Hawaiian area cruises are now nearing publication. No further conventional oceanographic work is anticipated, but information regarding variability and seasonal changes will continue to be collected on the fishing and biological survey cruises, and specialized oceanographic studies may be found desirable. There is as yet no clear correlation between any particular oceanic feature and the abundance of tuna.

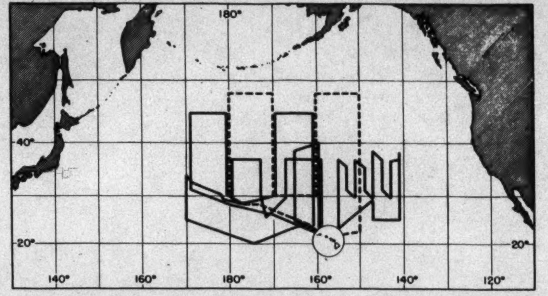


Fig. 3--North temperate area; heavy solid lines indicate tracks of completed POFI oceanographic cruises; dashed line indicates track of planned 1955 cruise during operation NORPAC

Knowledge of the oceanography of the north temperate central Pacific prior to POFI was similar to that of the tropical region; there were a few station lines available (primarily by the U. S. Navy vessels *Bushnell* and *Oglala*) for analysis, and only the general features of the circulation were understood. Only the first of POFI's three northern cruises has reached an advanced stage of analysis at this writing, and it is too early to indicate more than a general agreement with previous ideas about the area (Figure 3). An investigation into the relationship between the meteorology and the oceanography of this region is also being carried out. Fishing cruises are gathering data to correlate with the oceanographic observations; as yet there are few clues as to just what oceanic features most affect the concentration of tuna in these latitudes.

In the immediate future the POFI oceanographic program will complete the lines of investigation already undertaken and the considerable task of a comprehensive analysis of the data already collected. The continuing North Pacific survey will require a great deal of time, afloat and ashore, as will specialized problems to be investigated. The productive cooperation possible between physical and biological investigations is being amply demonstrated; if in the process vast oceanic areas are being described in heretofore unattainable detail it may be considered as a most welcome bonus.

APPENDIX 1--List of Publications Utilizing Oceanographic Data Collected by POFI

AUSTIN, THOMAS S., Mid-Pacific oceanography, part 3, transequatorial waters, Aug.-Oct. 1951, Spec. Sci. Rep.-Fish. 131, 17 pp., 13 fig., 49 sta., 1954a.

AUSTIN, THOMAS S., Mid-Pacific oceanography, part 5, transequatorial waters, May-June 1952, Aug. 1952, Spec. Sci. Rep.-Fish. 136, 86 pp., 1954b.

CROMWELL, TOWNSEND, Mid-Pacific oceanography, January through March, 1950, Spec. Sci. Rep.-Fish. 54, 9 pp., 17 fig., 53 sta., 1951.

CROMWELL, TOWNSEND, Circulation in a meridional plane in the central equatorial Pacific, J. Mar. Res., v. 12, pp. 196-213, 9 fig., 1953.

CROMWELL, TOWNSEND, Mid-Pacific oceanography, part 2, transequatorial waters, June-Aug. 1950, Jan.-Mar. 1951, Spec. Sci. Rep.-Fish. 131, 13 pp., 32 fig., 106 sta., 1954.

CROMWELL, TOWNSEND, R. B. MONTGOMERY, and E. D. STROUP, Equatorial undercurrent in Pacific Ocean revealed by new methods, Science, v. 119, pp. 648-649, 1954.

MONTGOMERY, R. B., Analysis of a Hugh M. Smith oceanographic section from Honolulu southward across the equator, J. Mar. Res., v. 13, pp. 67-75, 1954.

SETTE, O. E., Consideration of mid-ocean fish production as related to oceanic circulatory systems, J. Mar. Res., in press.

SETTE, O. E., and STAFF OF POFI, Progress in Pacific Oceanic Fishery Investigations 1950-53, Spec. Sci. Rep.-Fish. 116, 75 pp., 1954.

STROUP, E. D., Mid-Pacific oceanography, part 4, transequatorial waters, January-March, 1952, Spec. Sci. Rep.-Fish. 135, 52 pp., 1954.

Transactions, American Geophysical Union Volume 36, Number 5 October 1955

SOME RECENT OCEANOGRAPHIC SURVEYS OF THE GULF OF MEXICO

George B. Austin, Jr.

Abstract--An apparently semi-permanent, large scale, anti-cyclonic eddy repeatedly observed on four earlier oceanographic surveys was investigated in greater detail during Cruise 54-10 of the A. A. Jakkula, August-September, 1954. Evidence from the five surveys made in the region of the eddy indicates that the eddy is an integral part of the Gulf Stream system in the Gulf of Mexico. From the single ship survey of Cruise 54-10 an attempt was made (1) to locate and define the eddy and (2) to establish whether or not it was a temporary or permanent feature of the Gulf of Mexico and the Yucatan Current or to determine whether or not it changed physically in space and time or both.

Introduction--Early in 1951 a series of general oceanographic surveys of the Gulf of Mexico was begun under the sponsorship of the Office of Naval Research and through the U. S. Fish and Wildlife Service in Galveston, Texas, and the Texas A and M Research Foundation at College Station, Texas. By August, 1952, five cruises had been completed, covering all the deep-water area of the Gulf of Mexico and much of the shallow-water area. Emphasis had been placed on the physical oceanography of the Gulf by the Texas A and M group and on fisheries exploration or biological oceanography by the U. S. Fish and Wildlife Service group. The two groups worked together from the R/V Alaska during the period required for the five cruises.

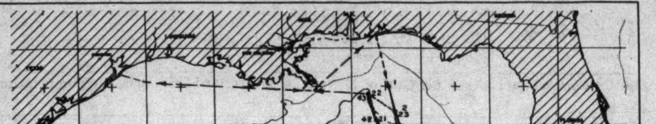
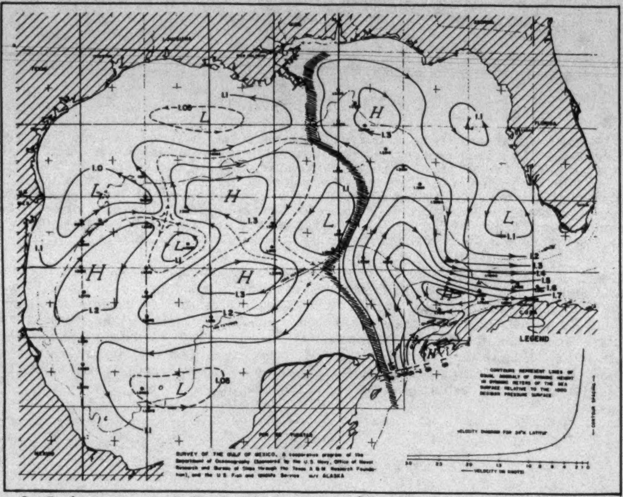


Fig. 1--Cruise 54-10 of the R/V A. A. Jakkula, August-September, 1954, 40 stations


H
L
1.0
1.1
1.2
1.3
1.06
1.05
LEGEND
CONTOURS REPRESENT LINES OF EQUAL ANOMALY OF DYNAMIC HEIGHT IN DYNAMIC METERS OF THE SEA SURFACE RELATIVE TO THE 1000 DECIBAR PRESSURE SURFACE
VELOCITY DIAGRAM FOR 24°N LATITUDE
CONTOUR SPACING
VELOCITY IN KNOTS

SURVEY OF THE GULF OF MEXICO, A cooperative program of the Department of Oceanography (Sponsored by the U.S. Navy, Office of Naval Research and Bureau of Ships through the Texas A & M Research Foundation), and the U.S. Fish and Wildlife Service m/v ALASKA

Fig. 2--Surface currents in the Gulf of Mexico as determined from dynamic computations

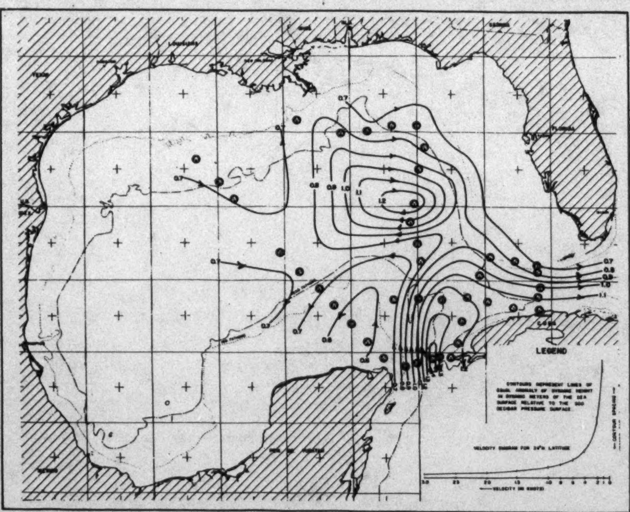

0.7
0.8
0.9
1.0
1.1
1.2
LEGEND
CONTOURS REPRESENT LINES OF EQUAL ANOMALY OF DYNAMIC HEIGHT IN DYNAMIC METERS OF THE SEA SURFACE RELATIVE TO THE 500 DECIBAR PRESSURE SURFACE
VELOCITY DIAGRAM FOR 24°N LATITUDE
CONTOUR SPACING
VELOCITY IN KNOTS

Fig. 3--Surface currents in the Gulf of Mexico as determined from dynamic computations of Cruise 4-2A

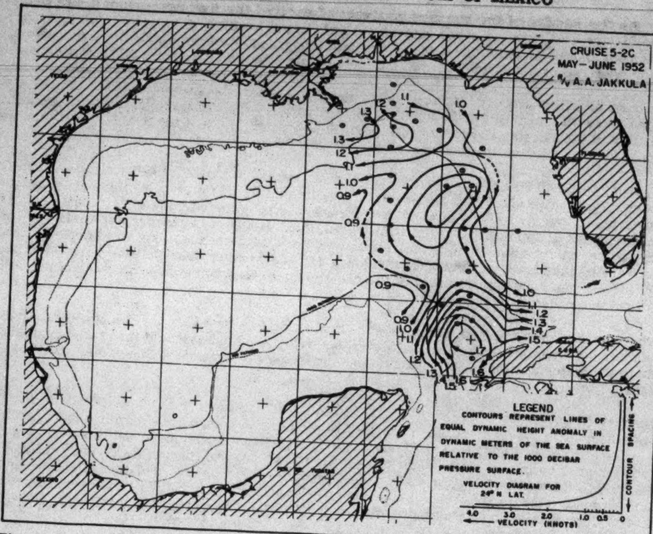

CRUISE 5-2C
MAY—JUNE 1952
R/V A. A. JAKKULA
1.1
1.2
1.3
1.0
0.9
1.4
1.5
1.6
1.7
LEGEND
CONTOURS REPRESENT LINES OF EQUAL DYNAMIC HEIGHT ANOMALY IN DYNAMIC METERS OF THE SEA SURFACE RELATIVE TO THE 1000 DECIBAR PRESSURE SURFACE.
VELOCITY DIAGRAM FOR 24° N LAT.
4.0
3.0
2.0
1.0
0.5
0
VELOCITY (KNOTS)
CONTOUR SPACING

Fig. 4--Surface currents in the Gulf of Mexico as determined from dynamic computations

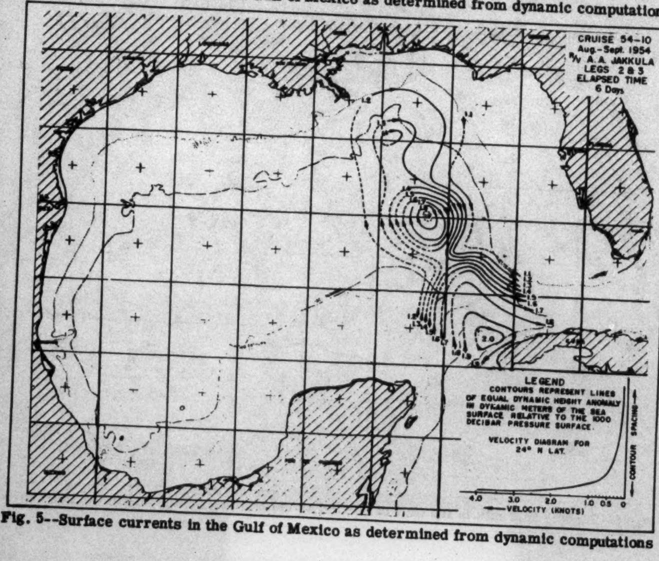

CRUISE 54-10
Aug.-Sept. 1954
R/V A. A. JAKKULA
LEGS 2 & 3
ELAPSED TIME
6 Days
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
LEGEND
CONTOURS REPRESENT LINES OF EQUAL DYNAMIC HEIGHT ANOMALY IN DYNAMIC METERS OF THE SEA SURFACE RELATIVE TO THE 1000 DECIBAR PRESSURE SURFACE.
VELOCITY DIAGRAM FOR 24° N LAT.
4.0
3.0
2.0
1.0
0.5
0
VELOCITY (KNOTS)
CONTOUR SPACING

Fig. 5--Surface currents in the Gulf of Mexico as determined from dynamic computations

As the results of the current analysis of each of the five cruises progressed, it was observed that one feature was repeated in the eastern central Gulf of Mexico. A large, well-defined anti-cyclonic eddy was observed to exist in the dynamic topography of three of the five cruises analyzed. The remaining two cruises had surveyed currents outside the eastern central Gulf of Mexico.

As a result of the circumstantial evidence found to support the existence of the eddy described above, a cruise was planned for the summer of 1954 to study the existence, location, permanence, and relation to the Yucatan Current of the eddy. This cruise, 54-10 of the R/V A. A. Jakkula, was sponsored by the Office of Naval Research through the Texas A and M Research Foundation.

Cruise 54-10--Cruise 54-10 departed Galveston, Texas, in August, 1954, for the eastern Gulf of Mexico. The cruise plan (Fig. 1) followed was quite simple. Two parallel lines of oceanographic stations running roughly NW-SE through the estimated location of the eddy were repeated to give a total of four lines of approximately ten stations per line. Standard oceanographic casts were made at each station, where water samples for salinity and oxygen determinations were collected and the usual reversing thermometer data were obtained. BT and weather observations were taken hourly. Loss of electrodes, housings, and part of the cable early in the cruise prevented use of the GEK for most of the cruise.

After the first line was run, six days were lost owing to a breakdown. The last three lines of stations were obtained without additional delay, however, and the results of those observations constitute the major portion of this discussion. Cruise 54-10 terminated September 10, 1954, in Galveston, Texas.

Discussion of results--Cruises 1-1A, 2-1B, and 3-1C (summer 1951) constituted the first complete oceanographic coverage of the entire Gulf of Mexico. A composite dynamic height contouring of the three cruises is illustrated in Figure 2. It is significant here though that the region of the eddy was covered by the dynamic height topography of two cruises (Cruise 1-1A and 3-1C). A small intense eddy to the north of the Yucatan Channel produces a strong anti-cyclonic effect on the Yucatan Current toward the northwest. A second but weak anti-cyclonic eddy is illustrated just south of Pensacola. It appears to be a continuing part of the Yucatan Current system, or at least a consequence

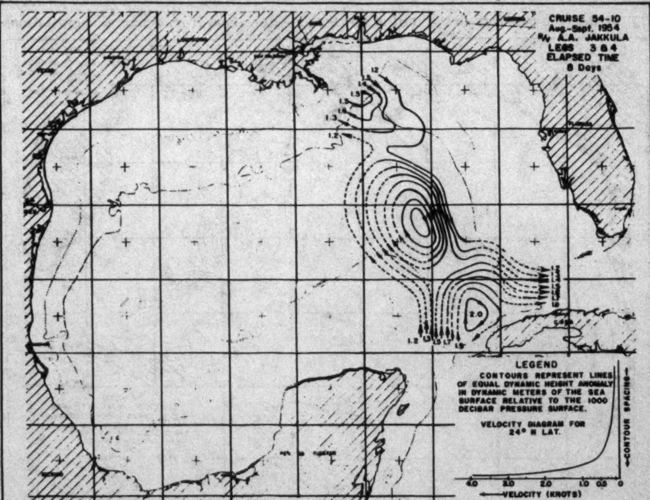

CRUISE 54-10
Aug.-Sept. 1954
R/V A.A. JAKKULA
LEGS 3 & 4
ELAPSED TIME
8 Days
1.2
1.3
2.0
1.5
1.7
1.9
LEGEND
CONTOURS REPRESENT LINES OF EQUAL DYNAMIC HEIGHT ANOMALY IN DYNAMIC METERS OF THE SEA SURFACE RELATIVE TO THE 1000 DECIBAR PRESSURE SURFACE.
VELOCITY DIAGRAM FOR 24° N LAT.
4.0
3.0
2.0
1.0
0.5
0
VELOCITY (KNOTS)
CONTOUR SPACING

Fig. 6--Surface currents in the Gulf of Mexico as determined from dynamic computations of that current. Since these two eddies are consequences of two separate cruises, the resulting composite analysis is at best weak, lacking continuity in time if not space.

Figure 3 for Cruise 4-2A (winter 1952) graphically shows the existence of a very large anti-cyclonic eddy in the region described above. The analysis here falls into the realm of actuality inasmuch as the period of the cruise in the region of the eddy was two weeks or less.

Figure 4 for Cruise 5-2C (summer 1952) again graphically displays the large anti-cyclonic eddy in the same region.

Figure 5 shows the dynamic height topography analysis of legs two and three of Cruise 54-10. Again a strong, well-defined anti-cyclonic eddy is inferred considering the extrapolation required by the cruise plan.

Figure 6 illustrates the dynamic height topography inferred from legs three and four of Cruise 54-10. Once again the well-defined anti-cyclonic eddy is very much in evidence but larger in size. It is, of course, significant that the topographic features of leg three are common to and greatly influence both analyses. The time required to cruise the three legs was two weeks. Leg one and the associated delay period totaled more than two weeks; therefore, the effects of the first leg on the current analysis were discarded after a preliminary investigation.

The eddy encountered on Cruise 54-10 was very intense as depicted by the contour spacing in Figures 5 and 6. Current velocities observed at sea were of the order of two and three knots in a region not commonly associated with the Yucatan Current (for example, the area of the eddy, in particular the eastern side of the eddy).

Of great interest also is the extent of the northward migration of the Yucatan Current before it curves toward the east and the Straits of Florida. This looping effect of the current in itself forms around a small anti-cyclonic eddy located near to the northwest coast of Cuba, and appears to be a permanent feature of the Yucatan Current pattern.

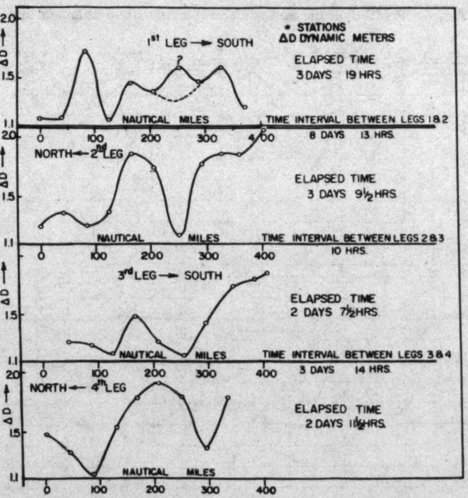


Fig. 7--Profiles of the sea surface from dynamic computations, total survey time 24 days, 12 1/2 hrs

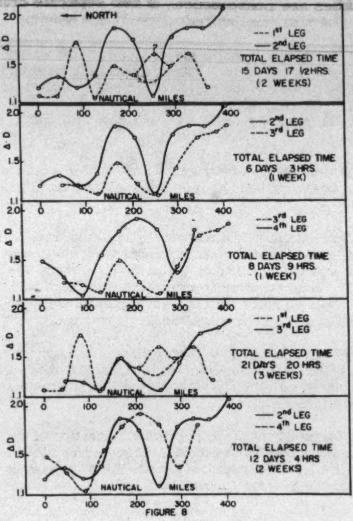


Fig. 8--Profiles of the sea surface from dynamic computations

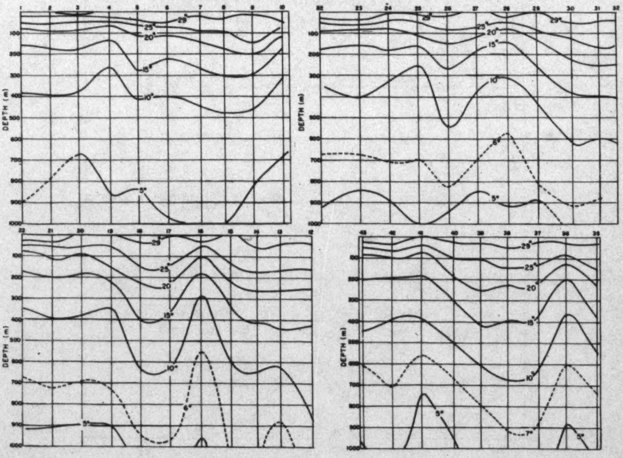


Fig. 9--Temperature-depth section

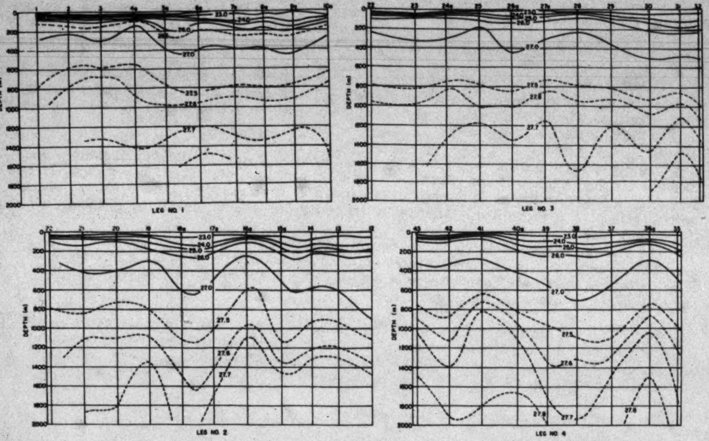


Fig. 10--σ_T-depth sections, Cruise 54-10, $\sigma_T = 1000(\rho_\theta - 1)$

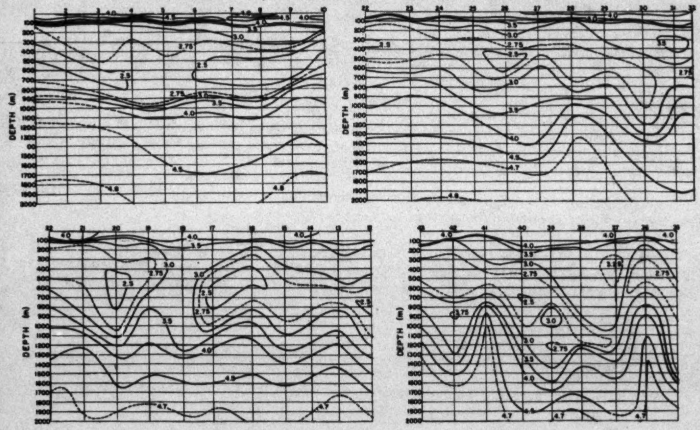


Fig. 11--Oxygen-depth sections, (ml/L)

A zone of current shear between the northern loop of the Yucatan Current and the large anticyclonic eddy farther to the north is of additional interest.

Profiles of the sea surface along the four legs of Cruise 54-10 are illustrated by Figures 7 and 8. The outstanding features of these presentations are the variations found in the sea surface elevation over such short distances. The profile of ΔD for the first leg is based on some doubtful data resulting from a few poor casts early in the cruise; pre-trips, doubtful and malfunctioning thermometers, and shallow casts all contributed to the questionable accuracy of the sea surface profile depicted here. For this reason the sea surface profile of the first leg was not used in contouring the dynamic depths as mapped in Figures 5 and 6.

Temperature-depth sections of the cruise are those illustrated by Figure 9. They reflect the eddy activity of the region described above. Figure 10, σ_t-depth sections also reflect indirectly these motions. Figure 11 presents a picture of the oxygen-depth distribution in continuous sections across the Gulf for the first time.

The sea surface profiles as inferred from the dynamic height anomaly computations were checked for tidal influences and effects. The predominant tide, diurnal for this region, the short range of the tide (two feet or less), and an investigation patterned after Defant, showed the tidal effects, if any, to be negligible in altering or distorting the dynamic height topography.

The average distortion which could be expected as a result of this investigation was ±5 dyn cm. This average distortion amounts to an error of about 3.3 pct in the region of the eddy. This is not sufficient to remove the existence of the eddy even at the most favorable conjunction of tide and station observations for such removal.

On the basis of the five cruises described, the results of the analysis of the physical data of these cruises and the information presented here, it is concluded that a semi-permanent or permanent feature of the Yucatan Current-Gulf Stream system is a large scale anti-cyclonic eddy centered at about 26°N, 86°W.

This eddy changes in shape, size, and intensity in time and space.

The exact nature of the changes that take place are not known at the present time. There is a need for additional detailed study of this current pattern, particularly if as suggested here the feature is permanent or semi-permanent. A multiple-ship survey of the region, making extensive simultaneous use of the GEK and Loran for fixes, would be a desirable approach to the problem.

Another possible approach could be detailed half-hourly or hourly Loran fix reports from commercial shipping in the area compared to their D. R. navigation as has been done for the Gulf Stream. Probably a combination of the two efforts would be the most desirable approach to the problem.

The Texas A and M Research Foundation plans other single-ship oceanographic surveys of the area, with increased use of GEK, BT, and Loran data as a means of investigating in greater detail the eddy described here.

One such cruise to the Yucatan Strait was completed early in April, 1955. The results of that cruise are not yet available, however.

(Contribution from the Department of Oceanography of the Agricultural and Mechanical College of Texas, Oceanography and Meteorology Series No. 52; based on investigations conducted for the Texas A. and M. Research Foundation through the sponsorship of the Office of Naval Research.)

Department of Oceanography
Agricultural and Mechanical College of Texas
College Station, Texas

(Manuscript received April 18, 1955; presented at the Thirty-Sixth Annual Meeting, Washington, D. C., May 2, 1955; open for formal discussion until March 1, 1956.)

Transactions, American Geophysical Union Volume 36, Number 5 October 1955

CALYPSO OCEANOGRAPHIC EXPEDITIONS

James Dugan

Abstract--Founded by J-Y Cousteau and directed by the French National Center for Scientific Research, *Calypso* Expeditions have added free diving to classic marine instrumentation. The *Calypso* research team, which with its Marseille center Office Française de Recherches sous-Marines, numbers fifty divers, seamen and technicians, employs the 320-ton research vessel, MS *Calypso*, and a 60-foot converted trawler, *Espadon*. The group employs underwater still and cinecameras and submersible television apparatus in both handheld and automatic depth units on cables. Carrying scientific parties up to ten people, *Calypso* since 1951 has undertaken a general monography of Abu Latt island in the Farsan Bank of the Red Sea; underwater excavation of a Greek cargo ship, sunk circa 205 B. C., off Marseille: a geodetic survey of the bottom of the Persian Gulf off Trucial Oman: hydro-archeological surveys in the Aegean and Ionian Seas; and many sorties of two or three weeks in the Mediterranean for biological, geological, and chemical studies. A continuing investigation of the deep scattering layer and bottom phenomena is being made with automatic electronic flash cameras built at Massachusetts Institute of Technology. About 30,000 photographs have been taken in the Mediterranean Sea, the Red Sea, and the Indian Ocean. These cameras are also used on the French Navy bathyscaphe FNRS 3. Camera stations of 3000 ft down have been attained. The DSL photo evidence has not shown a clear case for sonar interference by organisms. Photos made above and below the diffusion layer have often shown as many microorganisms, siphonophores, medusas, shrimps, etc., as in the layer itself. No larger athletic animals such as squids have been found in the photographs of the DSL.

Calypso Oceanographic Expeditions were created in 1951 by Jacques-Yves Cousteau, on special scientific leave from the French Navy Group for Undersea Study and Research. The Expeditions are sponsored by the Ministry of National Education and directed by a joint committee of the Ministry and the National Scientific Research Center under Louis Fage, director of the Institut Oceanographique in Paris. This committee also plans the research program of the French Navy bathyscaphe FNRS 3. *Calypso* Expeditions also receive disinterested private support and grants from the National Geographic Society.

The Expeditions are carried out in the twin-diesel ship *Calypso*, an ex-YMS class minesweeper of 320 tons with a 5000-mi range. Cousteau has converted her extensively for marine investigation with a 12-man aqualung diving team, a total crew of 21 and places for four scientists. Four more may be accommodated on short cruises. The ship employs classic depth instruments with the addition of undersea movie and still cameras, both hand-held and automatic electronic flash units. Before the stem *Calypso* is fitted with a steel tube leading to a two-man observation chamber on the forefoot, eight feet beneath the surface. A low freeboard and open afterdeck facilitate diving and winchwork. There is a drawbridge diving platform on the counter near the water and much diving reconnaissance is from two flat-bottomed metal launches, drawing five inches with a half-ton burden.

The divers have explored and taken artificially-lighted photos, films, and specimens beyond 200 ft down, but usually operate in the 90 to 130-ft range. Cousteau relies strongly on *Calypso*'s sonar installation, an NMC set on 18 KC, which is used for check against an Edo 185 with alternative frequencies of 12 and 34 kc. The latter has three transducers and five depth ranges, and also records sound waves sent up by submersible sonar fitted to the depth cameras. *Calypso* carries a fishscope, automatic pilot, maximum radar, automatic course recorder, and powerful generators for underwater lighting. The ship has two small marine biological points with sinks and an air-conditioned photographic laboratory. She has a collapsible decompression chamber, a ten-ton electric winch, a smaller gasoline winch, and a half-ton wine tank.

The Expeditions also maintain a 60-ft Marseille trawler, the *Espadon*, and a laboratory in Marseille, the Office Française de Recherches Sous-Marine, where experiments go on in pressure physiology, underwater photography and television, marine archaeology, and the development of depth vehicles. The work of the Expeditions is non-military, free of security regulations, and open to all students of the sea. *Calypso's* first cruise was to Farsan Bank in the Red Sea in 1951-52, where a party of ten scientists carried out a general monography of the uninhabited coral island of Abu Latt, under the direction of Pierre Drach, zoologist of the Sorbonne. Drach dived over 200 ft to study the ecology of fixed fauna on the reefs. The Expedition cleared an air strip on the island from which a plane made photo maps. The first published monograph of Calypso Expeditions, covering these studies, has recently appeared. Drach has published several papers on his researches in which he advocates the use of free diving as an oceanographic resource.

In the summer of 1952, the Expeditions turned to marine archaeology in the excavation of an ancient Greek cargo ship buried in fossil mud under 125 ft of water off Grand Congloué Island, Marseille. The sinking has been dated at 205 BC by Fernand Benoit, State archaeologist of Provence, who supervises the project. Calypso was endangered in mooring over the wreck, which is almost directly under a precipitous cape. To free the ship the operation was transferred to the island, where a ten-man billet and an engine house were built. An 80-ft boom was slung over the wreck to support the suction pipe used in excavation. During the first year a hand-held underwater television camera was devised to show the site to the archaeologists on the surface, and they could direct the divers by a submerged loud speaker. In over 2 1/2 yr of continuing work more than 3000 tons of mud have been piped out into a filter basket on the island. Nearly 9000 amphoras have been exhumed and about 15,000 pieces of fine Delian pottery.

In 1953 Calypso was joined by Harold E. Edgerton, Professor of Electrical Measurements at MIT, who had devised automatic electronic flash depth cameras for study of the deep scattering layer. The cameras were provided by the National Geographic Society. These earlier models consisted of a flash tube synchronized with a shutterless 35mm stop-motion camera in another tube. These units survived immersions of 3000 ft. They were usually set for four exposures a minute in a field of one square meter, six to eight feet from the lens. About 800 pictures could be made per immersion. Edgerton also used a silhouette camera with the flash and camera confronting each other in order to photograph a disc of water about 1 × 4 in. The latter produced little result, and it was felt that perhaps tiny marine creatures avoided the aperture as the mouth of some predator. The next year Edgerton rebuilt the silhouette camera to have the flash cross the camera field at a right angle and obtained useful photographs.

The first campaign on the DSL consisted of 17 camera stations in the Ionian, Aegean, and Ligurian seas and the Gulf of Corinth. Camera depths were controlled by sonar. The camera was lowered through the layer or layers (several times there were three diffusion layers recorded): it was stationed in the DSL and above it and below it; and it was hung stationary for the layer to pass the lens during the vertical migrations of dawn and sunset. Thick populations of micro-organisms, shrimps, medusas, and siphonophores were photographed, but often the census was as great above and below the DSL as in it.

In 1954 Edgerton continued his Calypso work with deeper and more powerful cameras to which he attached sonar transmitters to increase the accuracy of placement. These units could also be precisely stationed for photographs of the bottom by means of a dangling mercury switch. When it touched bottom the switch tripped and cut off the sonar ticks. On a three-week cruise in the summer with a party from the Endoume Marine Station under Jean-Marie Pérès, which investigated the submarine ridge between Tunisia and Sicily, Edgerton obtained photos of sea fans and other fauna in areas where Pérès' dredgings showed no traces of life.

The Edgerton cameras are in continuous use aboard Calypso and have been lowered in the Red Sea, Arabian Sea, Persian Gulf, and Indian Ocean. The Expeditions now have about 30,000 photographs of the scattering layer and the bottom, a number which vastly overtaxes the analysts. The photos may be plotted by reference to the sonar tapes which have been annotated and corrected during lowerings. The problem of the DSL remains for Edgerton and Cousteau as mysterious as before they began the photographs. Both men have descended in FNRS3 with Georges S. Houot, who in 1954 dived to 13,287 ft off Dakar. The French bathyscaphe is equipped with external Edgerton cameras, but Edgerton and Cousteau wanted to see the DSL for themselves. They found the biological 'soup' thicker below the indicated DSL than inside the layer.

In the first six months of 1954 Calypso cruised 35,000 mi in the Red Sea, Persian Gulf, and Indian Ocean. Cousteau conducted a submarine geodetic survey off the Trucial Oman coast of Arabia in depths varying from 20 to 200 ft. The geological party aboard used a marine gravimeter, a submarine jet hose and half-ton drop coring 'bombs.' Four coring pipes were shattered on the first four drops and were retrieved by divers. The limestone floor had a tough crust. Pairs of divers then obtained floor samples. One man held a chisel while the other hammered it. Four hundred such stations were completed in two months. The divers were furnished with an emergency refuge against sharks, an iron cage which they call 'the human zoo.' There were quite a few sharks, which did not, however, prove as bothersome as the four species of poisonous sea snakes which gathered inquisitively around the men and could slither between the cage bars with ease. Notions that the Persian Gulf is sterile were dispelled by sharks, snakes, shoals of rockfish, and even whales.

Leaving the Gulf, Calypso stopped several times along the Oman and Hadramaut coast and the Kuria Muria Islands for reconnaissance dives. The submerged littoral was found almost devoid of living coral and with few fish.

A party of zoologists under Gustave Cherbonnier of the Paris Museum of Natural History was landed for a month on Aldabra Atoll in the Indian Ocean, a remarkably preserved tropical island which has an estimated half million giant land turtles and myriads of unmolested sea and land birds, nesting in the mangrove jungles of the lagoon. Marine specimens were obtained by selective dynamiting. Divers placed charges in a submerged reef to kill or stun in a given radius. One such explosion in a 15-ft hemisphere yielded 167 fish of 33 species. Ninety per cent of them were retrieved from the bottom.

In Madagascar Calypso picked up James Millot, director of the Scientific Institute of Madagascar and the Laboratory of Comparative Anatomy of the Sorbonne. He is a specialist in the coelacanth (Latimeria chalumnae), the living fossil fish found in the Comor Islands northwest of Madagascar. The ship circumnavigated the islands in concentric patterns, building up an echo-sound chart of the coelacanth haunts, and obtained environmental information with Edgerton cameras and bathythermographs. All ten specimens of the fish have been handlined from depths exceeding 500 ft at night in the months November to January. It was shown that the temperature at these depths is 26° C lower than the surface. Later the death of the first coelacanth captured alive, which lived 19 hr in a swamped whaleboat, was attributed by Millot to photophobia and severe change in temperature and pressure.

Last summer (1954) Calypso made three sorties in the Mediterranean with parties from the Endôume, Villefranche, and Drago marine stations. The latter station at Banyuls-sur-Mer is where the first underwater photographs were made by Louis Boutan in the 1890s.

Although Calypso expeditions have furnished a great deal of evidence on various problems in little more than three years of activity, results are only beginning to be published. The organization has the means to work at sea nine months of the year, a skilled cadre to assist scientists, and is constantly adapting and designing tools and techniques for oceanography. Free diving and several types of underwater photography are the most important of these contributions.

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BRITISH COLUMBIA INLETS

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Abstract--The Institute of Oceanography of the University of British Columbia has been studying the oceanography of the inlets of the British Columbia coast since 1951. Temperature, salinity, and oxygen content are determined by routine methods on board ship. Internal waves have been studied with bathythermographs in deeper water, and with a resistance thermometer near the surface. Vertical current profiles have been measured with CBI drags and Ekman meters, while surface currents have been recorded by photographing dye patches. The possibilities of identifying water masses by plankton distribution or by ionic ratios are also being investigated.

The British Columbia mainland coast extends some 500 mi from the United States border northwest to Alaska. Two large island groups and many smaller ones lie off the main coast, the shoreline throughout being predominantly rocky. In striking contrast to the Pacific Coast to the south are the many long, narrow, and deep indentations in the British Columbia coast (Fig. 1). On the charts these have a variety of generic names, such as arm, canal, channel, sound, inlet, but for convenience the last has been adopted.

After its formation in 1949 the Institute of Oceanography of the University of British Columbia elected to study these inlets as its main task. At that time, Alberni Inlet on the west coast of Vancouver Island had been examined in detail by TULLY [1949], who had also made limited observations on several other inlets in the same region. CARTER [1933] had made short surveys of a few of the southern inlets of the 28 in the mainland coast but little was known of the others.

The first cruise made by the Institute was extensive. In May-July 1951, the majority of the longer inlets were surveyed using the CNAV Ehkoli. This 85-ft vessel is manned by a civilian crew and has accomodation for five scientists. She carries a Fjarlie electric winch with continuously variable gear drive for water-sampling and plankton hauls, and a Kelvin sounding winch for the bathythermographs. Hydrographic stations were occupied every five miles along the inlets to determine the salinity, temperature, and oxygen distribution. The sampling depths in the upper 50 m, where the major salinity changes take place, were adjusted to delineate the halocline as well as possible. Since the thermocline and halocline are closely associated, a bathythermograph cast was made before the bottle cast to assist in selecting suitable bottle depths. At alternate stations bottom samples were taken and plankton tows made.

Temperatures were measured with Richter and Wiese thermometers and bathythermographs, a shallow cast with the latter being made as the messenger was released. Since it was relatively easy to maintain the wire angle vertical to within a few degrees, unprotected thermometers were rarely used. Salinity was determined on shipboard by the Mohr method, and oxygen by the Winkler method. A target accuracy of 0.02 pct for salinity was considered sufficient, particularly in the upper layers where short period changes are common. The in situ determination of salinity was adopted because the exploratory nature of the cruise made it desirable to be able to repeat observations in locations where results appeared anomalous.

The scientific complement for this cruise was two scientists and three assistants. Three hundred stations were occupied in a 3,000 mi cruise in three months.

Since the results obtained from this first cruise have formed the basis for subsequent work, they will be summarized. The inlets range from five to 90 mi long, and from 0.5 to 3 mi wide. The average midchannel depth is about 330 m and the maximum known is about 740 m. The sides of the inlets are steep, 45° being common, and the bottom is flat. It consists chiefly of a deposit of fine glacial silt from the rivers and has very little organic content. Shallow sills in the inlets are uncommon. In the larger inlets the shallowest sills are about 30 m for the Seymour-Belize group and 50 m in Knight and Observatory, while the rest are over 200 m. All the long inlets have large rivers at the head and are positive estuaries in the sense that run-off and precipitation exceed evaporation.

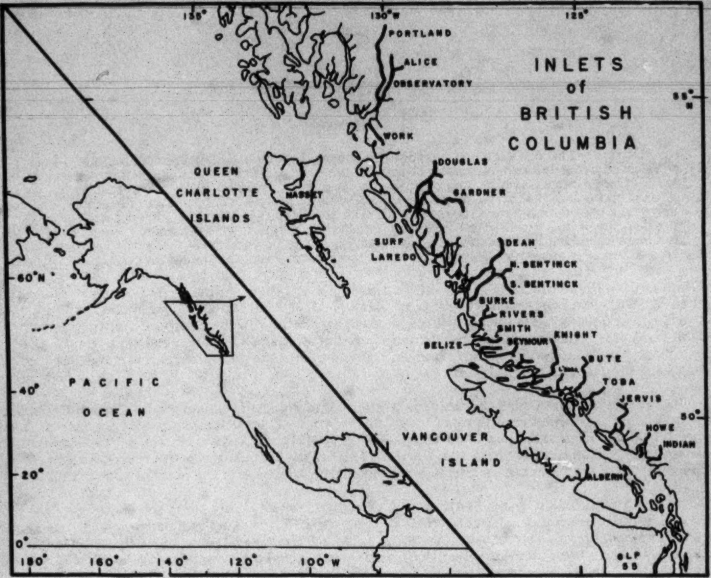
INLETS of BRITISH COLUMBIA
135°
130°W
125°
55° N
50°
PORTLAND
ALICE
OBSERVATORY
WORK
DOUGLAS
GARDNER
QUEEN CHARLOTTE ISLANDS
MASSET
SURF
LAREDO
DEAN
N. BENTINCK
S. BENTINCK
BURKE
RIVERS
SMITH
BELIZE
SEYMOUR
KNIGHT
BUTE
TOBA
JERVIS
HOWE
INDIAN
VANCOUVER ISLAND
ALBERNI
PACIFIC OCEAN
60°N
40°
20°
0°
180°
160°
140°
120°
100°W
GLP 55

Fig. 1--Location of British Columbia Inlets

The surface salinity in summer increases from about 1‰ at the head to 10 to 28‰ at the mouth, but below about 30 m the longitudinal gradients are small. At the surface there is a homogeneous layer and below this the halocline at five to 12 m. The salinity reaches 90 pct of the deep-water value by 20 m and thereafter increases slowly [PICKARD, 1953a, TABATA, 1954].

The temperature of the deep water ranges from seven to eight degrees Centigrade, while at the surface it rarely exceeds 15°C because the river runoff is cold, being chiefly from glaciers. Subsequent observations have shown that annual fluctuations are slight below 100 m. Some inlets, particularly Bute, show a temperature minimum at 60-80 m in spring and summer.

The oxygen saturation of the surface layers [PICKARD, 1954b] is usually close to 100 pct but often rises to 170 pct in the presence of phytoplankton. The saturation decreases to 40 to 60 pct by 200 m and changes little below this. Values as low as 22 pct have been observed in Jervis Inlet, which is a long inlet with no sill but which does have a smaller runoff than the remainder of the long inlets. An oxygen minimum of six per cent at 70 m in Belize Inlet was the lowest value recorded on the mainland coast (similar observations in Belize Inlet had been made previously by THOMPSON and BARKEY [1938].

The similarity in water structure in the long inlets suggested that it would be sufficient to limit detailed study to one or two, and the more accessible southern ones, Bute and Knight, were selected. During the 1952-54 summer cruises, routine temperature and salinity measurements were continued, and in addition two special features were examined: internal waves and current profiles. HMCS Cedarwood, a 185-ft vessel manned by naval personnel and operated by the Royal Canadian Navy entirely for marine research, was used. She has accommodation for up to eight scientists and carries a medium-duty and two light-duty winches. The Fjarlie medium duty winch uses a Chrysler automobile engine with fluid drive and gear box to two drums for 3/16 and 3/8-in wire, the whole being mounted as a unit for ease of transfer to other vessels.

The mid-depth internal waves in Bute [PICKARD, 1954a] have been observed by making series of bathythermograph casts at 15 or 30-min intervals for 20 to 70 hr. The presence of the temperature minimum makes it possible to follow the vertical movements down to 120 m. They have amplitudes of as much as 20 m and have fairly constant phase relationship to the surface tide. Salinity measurements reveal periodic oscillations of a similar character although the records are not as detailed. Simultaneous temperature series taken at mid-inlet and about one quarter of the length from the head showed about 180° phase difference and a smaller amplitude at the second station. The individual readings of isotherm depth show a marked short-period scatter about the long-period mean oscillation. This was at first attributed to bathythermograph deficiencies, but a review of some casts taken with two bathythermographs tied together suggests that a part of this short period fluctuation may be real and due to turbulence. It is hoped to investigate this further with a view to obtaining information on eddy size. No really satisfactory method for eliminating the effect of the internal waves from the hydrographic station data has been devised yet.

Internal waves in the upper layer have also been observed, particularly in Knight Inlet, with the maximum amplitude apparently in the halocline. Since a marked thermocline accompanies the latter, the vertical oscillations of a selected isotherm have been followed by means of a rapid-reading electrical thermometer. This uses a Type 14B thermistor in a bridge circuit arranged to read temperature directly by the out-of-balance current through the meter. Using a marked cable the vertical movement could be followed to ± 10 cm, the depth being recorded at 15-sec intervals. Amplitudes up to nine meters about a mean depth of eight to ten meters have been measured, with periods of one to four minutes and wave-lengths of 75 to 200 m. The internal waves give rise to conspicuous bands of ripples and slicks on the surface, and the wavelengths have been estimated relative to ship's length when anchored, or by time and speed when running. The figures for period are the least significant because the waves are most common when the surface layer is ebbing and the underlying water flooding. The question then is whether the period should be measured relative to the surface or to the deeper water. At times the waves have remained substantially stationary relative to the shore for 15 min.

Anchoring for current measurements has presented something of a problem in the deeper inlets. Attempts to hold Cedarwood stationary by anchoring bow and stern have met with limited success because of her proclivity for lying beam on to the wind. Since this always blows along the inlet she then lies across the current and drags anchors in the soft mud bottom. The most practical method has been to be satisfied with a single anchor and to limit measurements to light wind conditions, particularly at night. In addition it is our practice to determine the ship's movement by three-point fixes on the shore at the beginning and end of every current measurement.

Current measurements down to ten-m have been made chiefly with CBI drags, while Bergen Nautik Ekman current meters have been used beyond this depth. Two Kahl meters with split bearings for series use on the line have been used to a limited extend. A few measurements have been made down to 300 m, but the majority are above 200 m depth.

In 1954 currents were measured in Georgia Strait at 35 cm above the bottom in depths of 50 to 200 m. For this an Ekman meter was mounted in a frame and arranged to record only when the wire was slacked off. The only difficulty experienced was when strong surface currents caused a large wire angle. This made it difficult to be sure whether or not the meter was on the bottom. This difficulty could have been avoided by using greater weights on the frame, but the light-duty winch in use precluded this. Currents up to one knot were noted. In some cases the major component was directly on-shore at a station only 1/2 mi from the shore.

To investigate currents in the surface water a visual method has been tried [PICKARD, 1953b]. A series of patches of dye was laid from a launch in a line across the inlet. (A garden syringe and a bucket of dye served well.) The motion of these patches was then watched and recorded photographically from a position on the side of the inlet. The steep sides permitted observing positions at an elevation of 1000 ft with the angle of depression to the far shore being eight degrees and to the near shore 45 to 50°. The last figure indicates that the observing stations were only attained after the expenditure of some physical effort, particularly as the undergrowth was often very dense. In fact, the chief difficulty was not to attain sufficient altitude but to find a suitable vantage point, such as a rocky outcrop, to allow one to get far enough out of the trees to permit a good view of the water.

The 35-mm camera records were analyzed by projecting with a short-focus lens onto a screen placed at the same angle to the projector as the sea was to the camera lens. The use of larger frame size cameras would have permitted the use of oblique grids for direct analysis, but the latter process would have been more laborious. The projection method was less exact but quickly yielded a plan record of the dye patch movements from which speed and direction could readily be obtained. Even simple visual observations of the patch movements was valuable, and the technique can be recommended if it is desired to obtain a preliminary idea of the character of the flow. This is useful in a tidal inlet preliminary to establishing current stations, in order to avoid back eddies. In some cases, in the present experiments, sharp shear zones were discovered which would probably have been missed if only a limited number of current stations across the inlet had been made.

The most satisfactory dyes were found to be Uranine (sodium fluorescein), giving a green-yellow color, and Rhodamine, showing pink. Aluminum powder forms very conspicuous patches but it is relatively expensive and is difficult to handle tidily. In addition it remains on the water surface and indicates the motion of the surface skin only. The differential motion between aluminum and dye in the presence of a breeze was conspicuous. If it was desired to distinguish between the colors of the dyes it was advantageous to use Kodachrome film, but otherwise panchromatic film with a yellow filter (K.2) was adequate. To aid in orienting the photographs it was necessary to have at least two conspicuous marks on the far shoreline, and to measure the angles of depression of these from the observing site with an Abney level. If the distance between the marks could be measured this served as a baseline for scaling the records, but otherwise the altitude of the observation point measured with a sensitive altimeter was used.

In 1953 the study of the inlets was extended to those on the west coast of the Queen Charlotte Islands. Regular hydrographic stations were occupied, but more effort than on previous cruises was devoted to biological work which was directed by R. F. Scagel. The CGS Cancolim II was operated by the Defense Research Board for this summer after her return from the Arctic the previous year. F. G. Barber, of the Pacific Oceanographic Group, was Master and in charge of physical oceanography. His crew consisted entirely of university students who doubled as ship's crew and oceanographic assistants.

The biological studies have had two objects: to determine the distribution of species along the coast, and to investigate the possibility of using both the qualitative and quantitative distributions as a means for identifying water masses and for yielding information on circulation. For the zooplankton, standard net collecting methods are employed. For the phytoplankton, Scagel uses a pump and hose for collection to depths of 100 m, and uses pigment analysis for quantitative determination. In addition, studies of the benthos in the upper littoral zone are being made in relation to chemical and physical conditions. One of the objects is again to use the distribution of genera and species as indicators of average and extreme water conditions, particularly in regions which cannot be visited frequently for direct observation.

In the chemical field, the ionic ratios of potassium and calcium to sodium in both river and sea water are being measured by M. Kirsch with a view to providing a tracer technique to aid in studying mixing in the inlets. Quantitative determinations are made with a Beckman DU Spectrophotometer with flame and photomultiplier attachments. Although much of the work has been done in the laboratory it is worth noting that it has been shown to be quite practicable to use this equipment without modification on board ship for a good proportion of the time when in the inlets.

The program for future work includes:

(1) Continuation of serial observations of salinity and temperature to determine appropriate mean conditions, the range of variation from the mean, and possible long term fluctuations.

(2) More intensive measurements of vertical profiles of currents at several positions along inlets, with particular attention to the greater depths.

(3) The investigation of glacial-silt distribution and deposition in the upper layers, light intensities, and particle distribution in the deep water as a possible aid to determining the deep water circulation.

(4) The investigation of oxygen distributions in the vicinity of kelp beds, associated with phytoplankton activity, and also near the heads of the inlets where an oxygen maximum is often observed just below the halocline.

(5) The continuation of observations on the distribution of benthonic organisms in the upper littoral zone and correlation with the physical chemical environment.

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THE DANISH OCEANOGRAPHIC AND FISHERIES RESEARCH VESSEL DANA, AND HER POST-WAR PROGRAM

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Abstract--This paper describes the origin and the present administration of the Danish Ministry of Fisheries' research vessel, Dana. The dimensions, the living, working and storage spaces, and the fundamental research equipment are also described. Plans of the ship are presented. The program of the Dana for the postwar years is briefly reported, including operations in the North Sea, the Faeroe Islands area, the North Atlantic and Davis Strait sections, and the Greenland west coast area. Station charts of selected operations are presented in conjunction with the above. Proposed future operations are discussed.

Introduction and background--For many years the Danish Ministry of Fisheries has sponsored and promoted fishery and oceanographic investigations, especially in the North Atlantic and in the home waters of Denmark, the Faeroe Islands, and Greenland. The Royal Danish Research Ship Thor was employed for such investigations from 1903 to 1913, followed by the little motor schooner Margrethe in 1913. Immediately after World War I, the Danish Commission for Investigation of the Sea was able to borrow a newly-built, four-masted schooner of 550 tons from the East Asiatic Co. of Copenhagen. This vessel was the M/S Dana I, utilized in 1920 and 1921 on several North Atlantic cruises of primarily biological nature, under the capable leadership of Johannes SCHMIDT [1929].

In 1921-1922 a trans-Atlantic expedition was instigated, employing the Research Steamer Dana II, a former British minesweeper purchased by the Danish government and converted into a research vessel. This expedition was more extensive than the earlier ones, and included a considerable number of hydrographical observations in addition to the continuation of the biological program [JACOBSEN, 1929]. In the ensuing years the Dana II was occupied with numerous expeditions, including the noteworthy, 'round-the-world cruise in 1928 to 1930 [THOMSEN, 1937], but the vessel unfortunately was sunk by a collision in the North Sea in 1935. The results of the Dana I and II have been published by the Rask-Ørsted Fund and the Carlsberg Foundation in Copenhagen in the series Dana Reports.

The program from 1946 to 1950--The present primary research vessel of the Danish Ministry of Fisheries is the Dana III, built in 1938 and utilized through the Ministry's research establishment, Danmarks Fiskeri- og Havundersøgelser, in the continuation of the fishery and oceanographic research program.

World War II halted all major activities of the ship, but in 1946 she started her postwar investigations with a two-month cruise to the North Sea, the Faeroe Islands, and across to Norway.

In 1947 the ship made a four-month summer cruise, working in the North Sea, the Faeroe Islands region [HERMANN, 1949a] and westward to Greenland. The North Sea investigations included three latitudinal hydrographic sections following the international sections Q, R and S adopted by the International Council for the Exploration of the Sea [EGGVIN, 1949].

A second four-month summer cruise was completed in 1948, with investigations in the North Sea (including the international R and S sections), and in the Shetland, Faeroe [HERMANN, 1949d], Iceland [HERMANN, 1949c] and southeast Greenland regions [HERMANN, 1949b]. Sections north of Scotland and of Iceland were taken in an attempt to find a correlation between hydrographic conditions and the occurrence of the Icelandic-Norwegian herring shoals. It was found that great herring shoals occurred north of the Faeroes in the boundary between the warm Atlantic water and the cold water of the East Icelandic Current [TANING, 1951a, 1952].

The Dana was rebuilt in 1949 and therefore was not in commission that year. Her 1950 cruise was again a summer cruise, although beginning in mid-April, slightly earlier than the previous postwar cruises.

The North Sea sections and the section between the Shetlands and the Faeroes were retaken, and investigations around and north of the Faeroes were continued [HERMANN, 1951b]. Herring shoals were noted by echo-sounder and were compared with the hydrographical conditions [TÅNING, 1951a]. The 62° North parallel between the Faeroes and East Greenland [HERMANN, 1951c] was again worked, and a new area of investigation was added in the form of hydrographic sections across the West Greenland Current [HERMANN, 1951c], combined with the tagging of cod and the collection of fish fry by use of stramin nets [HANSEN, 1953,1954; TÅNING, 1951b].

The positions of those hydrographic stations taken west of the North Sea in 1947, 1948, and 1950 are shown in Figure 1.

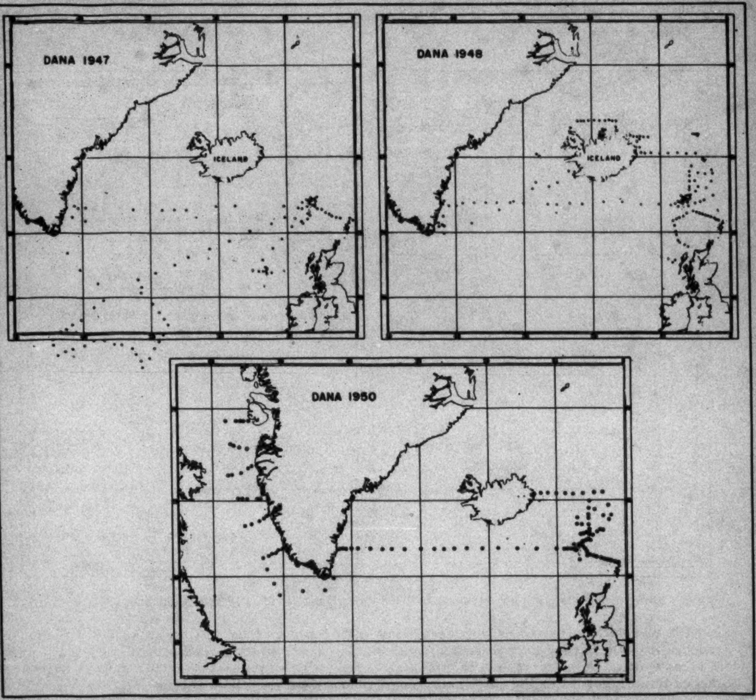

Fig. 1--Hydrographic stations taken by the Dana in 1947, 1948, and 1950

The program from 1951 to 1954--Two cruises were made in 1951, the first expedition being to the North Sea in April to June, followed by the working of the Shetland-Faeroe section, and sections west and north of the Faeroes [HERMANN, 1952]. Herring shoals were again located by echo-recording in these latter sections. The second cruise of that year began in November, and continued the hydrographic investigations and echo-recording of the herring shoals north of the Faeroes, returning to Denmark in mid-December.

In 1952, 1953, and 1954, the programs were essentially the same as in previous years, with work in the North Sea in April and May, and hydrographic investigations in the herring area north of the Faeroes in June [ANDERSEN, 1954; HERMANN, 1953b; TÅNING, 1953, 1954]. The expeditions then proceeded along 62°N latitude to Greenland [HERMANN, 1953a, 1954a] and across the Labrador Sea [HERMANN, 1954b]. Numerous hydrographic observations and cod studies were then made in the West Greenland Current [HERMANN, 1953c], where temperature fluctuations are of major importance to the stock of cod in that area.

In 1952 and 1954 sections were also worked from Kap Farvel to West Ireland in August, followed by another month of investigations in the North Sea. The hydrographic stations occupied from 1951 to 1954 are illustrated in Figure 2.

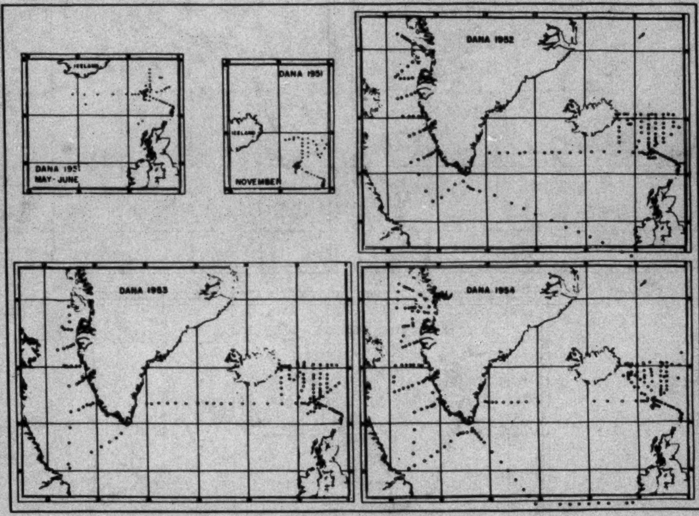

Fig. 2--Hydrographic stations taken by the *Dana* in 1951, 1952, 1953 and 1954

The investigations in the herring area north of the Faeroes from 1951 to 1954 were made in cooperation with Norwegian and Icelandic research vessels, working northward of the *Dana*'s area of investigation. A rendezvous of the three research vessels at a nearby harbor was normally arranged immediately after the survey, in order to compare and discuss results.

The future program--The future program of the *Dana* is expected to be a continuation of these recent hydrographical-biological investigations in the North Sea, the herring area north of the Faeroes, the West Greenland Current area, and pertinent sections between areas.

The ship--The third *Dana* is a single screw ship of about 500 tons, approximately 180 ft long. She normally carries a crew of 22, plus a scientific complement of six. Her cruising range is about 6000 mi, with a cruising speed of ten knots. The power plant is a 700-hp diesel engine, and until recently had an auxiliary coupling to an electric generator and motor to enable the rpm on the shaft to be reduced to a minimum while on station. As this coupling gave considerable trouble, it has now been removed and the hydrographic wire angle is satisfactorily maintained near zero by periodically starting and stopping the engine in close coordination with proper rudder control.

The scientific spaces and equipment--For scientific work the Dana is equipped with a hydrographic laboratory, biological laboratory, 'deck' laboratory, darkroom, office, and quarters for the six scientists. The laboratories are completely equipped with sinks, fresh and salt water, stowage cabinets and drawers, and other minor but necessary facilities.

The basic hydrographic and trawling equipment is invested in: (1) a large trawling winch forward, with a double drum, gypsy head, level-winders and proper leads and A-frames for trawling over the starboard side; (2) a variable-speed hydrographic winch with boom, used for lowering and raising up to 10,000 m of hydrographic wire; (3) a medium hydrographic winch rigged for towing; and (4) a smaller high-speed hydrographic winch with boom, holding up to 500 m of wire. These hydrographic winches are all located on the port side of the ship. Figures 3 and 4 illustrate the relative locations of these spaces and winches.

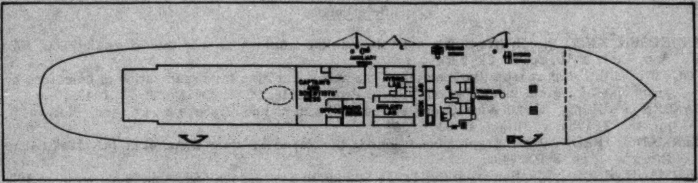

Fig. 3--Outline deck view showing location of major scientific spaces and winches

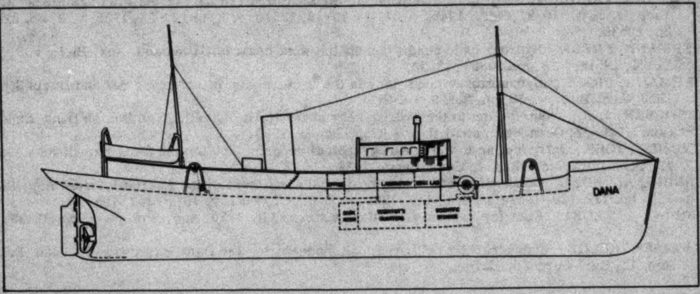

Fig. 4--Outline profile view showing location of scientific spaces and trawling winch

Hydrographic observations are generally made at standard depths, employing an insulated water bottle on the small winch, and a series of Knudsen bottles (with reversing thermometers attached) on the large winch. Salinities are determined in the hydrographic laboratory on board, time permitting, using the customary Knudsen method, and phosphate samples are drawn for the shallower depths and determined by the Nessler tube method. Samples for dissolved oxygen analysis are usually drawn for only the greater depths, and after proper 'pickling' according to the Winkler method, they are preserved by a water seal in a double glass container for later determination ashore.

The deck laboratory is primarily used for the initial sorting of trawl catches and for such operations as measuring, sexing, and examining the stomach content of fish. Plankton catches are primarily treated and sorted in the biological laboratory, and samples for productivity measurements by the Steeman-Nielsen carbon-14 method are initially processed in a small laboratory below decks.

The Dana has recently obtained the deep sea echo-sounder that was specially built by Kelvin and Hughes for the Galathea's recent expedition. An American Bendix fathometer is used for shallower work (recording to 400 fm). Among the more important other navigational instruments are radar, gyro compass, radio direction finder, and the Decca Navigator. The Dana also has a bathythermograph, which is only used while lying to in order to decrease chances of loss, and a continuous surface temperature recorder manufactured by Negretti and Zambra.

Publication of results--The results of the Dana investigations are periodically published in the Annales Biologiques and Journal du Conseil Permanent International pour l'Exploration de la Mer, and station data are published in the Bulletin Hydrographique of the same organization. Short reports of the cruises and investigations are published annually in the Fiskeriberetning (Fishery Report) of the Danish Ministry of Fisheries, and occasional papers resulting from the Dana investigations are also published by the Dana's parent institute, Denmark's Fishery and Sea Researches, in Meddelelser fra Danmarks Fiskeri- og Havundersøgelser.

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REPORT OF THE COMMITTEE ON INFILTRATION, 1954-1955

Leonard Schiff, Chairman

1955	1956	1957
E. H. Kidder	H. L. Cook	V. S. Aronovici
P. B. Rowe	H. W. Lull	J. H. Brown
N. L. Stoltenberg	D. E. Whelan	G. R. Trimble, Jr.

Reports from the committee members and others follow in abstract. Names and addresses of contributors are given as references for readers. The Chairman has complete reports on file.

Infiltrometer work--Some studies are stressing techniques and reliability of the infiltrometer. A study is being initiated using the double ring technique on a number of soils ranging in texture from coarse sands to clays (H. R. Haise and Neil Dimick, Fort Collins, Colo., Agricultural Research Service and Angostura Project, S. Dak., respectively). It is planned to use about 20 double ring infiltrometers at each site and to sample the soil thoroughly within each infiltrometer ring for subsequent physical analysis. It is hoped to isolate some of the physical factors affecting infiltration. Attempts will be made to determine the number of samples needed to account for soil variability. Another study is now underway in Eastern Oregon to determine the reliability of the double ring infiltrometer for estimating field intake rates under different methods of irrigation (F. M. Tileston, Agricultural Research Service, Ontario, Ore.).

Initial tests with the Rocky Mountain Infiltrometer have been completed on four open and four fenced watersheds at Badger, Washington (G. T. Turner, Forest Service, Grand Junction, Colo.). These tests are to be repeated at five-year intervals for 20 years for changes in infiltration due to livestock exclusion.

Infiltrometer runs coordinated with field studies at Merced, California, are being used to determine the influence of crops, time of irrigation, and soils on infiltration, (D. C. Muckel, Agricultural Research Service, Berkeley, Calif.). Average infiltration rates on pasture land were fairly consistent during the irrigation season and varied considerably with some crops due to cultural practices. Infiltrometers are being run on soils treated with gypsum and where hardpan has been broken mechanically.

A trailer-mounted, sprinkler-type infiltrometer is being used on about 10 soil types for the purpose of designing irrigation systems (G. M. Horner, Agricultural Research Service, Pullman, Wash.). Simulated rainfall from portable equipment is also being applied to test plots 2 feet square located within a circular area of 13 square feet on range lands (Frank Rauzi, Agricultural Research Service, Laramie, Wyo.). Infiltration tests conducted on six experimental native pastures showed significant differences between 'light' and 'heavy' use of pastures. Ranges with a greater quantity of both vegetation and mulch averaged higher intake rates than those with less protection.

Infiltrometer runs of long duration under a constant surface head were found to yield infiltration rates consistent with those of large spreading areas, (Leonard Schiff, Agricultural Research Service, Bakersfield, Calif.).

Portable equipment has been developed for measuring rain drop dispersibility, infiltration and air permeability on the same field sample of soil in place (Don Kirkham, Iowa State College, Ames, Iowa).

Infiltration relative to runoff--One-square-foot rings are being used to determine infiltration rates and runoff (J. H. Brown, Los Angeles County Flood Control District, Los Angeles, Calif.). The soil is brought to saturation by sprinkling, then drops applied at rates which exceed the infiltration capacity and the runoff is conducted by a drain tube from the ring to a measuring graduate.

Comparison between recorded hydrographs under saturated soil conditions and hydrographs computed by the rational runoff formula, using test-plot coefficients, show a correspondence between peak flow approaching the accuracy of stream-flow gagings.

Infiltrometer data collected as a part of the Little Sioux flood control survey in 1940-41 are being analyzed for the following points (Don Kirkham, Iowa State College, Ames, Iowa). (1) For a particular soil type and crop cover the parameters in the infiltration-capacity equation $f = f_c + (f_c - f_c)e^{-kt}$ are being determined. (2) For a given soil type and crop cover the above parameters are being related to antecedent rainfall (a seven day antecedent period is being considered). (3) Rainfall data at Sioux City, Iowa (May to September, 1907-53) are being analyzed for the seven-day antecedent rainfall with respect to an excessive storm and for the pattern of that storm. From the results of the above points an attempt will be made to predict the flood flow (volume) for actual watersheds and to attach a probability statement to such an estimate.

Infiltration relative to water spreading--Mechanical, vegetative, cultural, chemical and soil conditioner treatments are being made to increase infiltration rates on ponds and basins of spreading areas, (K. W. Campbell, Kern County Land Co., Bakersfield, Calif.). Special attention is given to treatments on 42 one-acre plots. Shafts, trenches, and pits which cut through less pervious material and reach coarse sand streaks are under observation for rates and clogging factors. Series of nests of piezometers have been installed in conjunction with many field operations to record losses in hydraulic head, to chart development of perched water tables and to determine groundwater movement.

In cooperation with the Kern County Land Co., North Kern Water Storage District, California Agricultural Experiment Station, and the California Division of Water Resources, the Agricultural Research Service staff at Bakersfield, California (Leonard Schiff, E. S. Bliss, and C. E. Johnson), are conducting concurrent field and laboratory tests on water spreading. Water and soil treatments and operational procedures that affect infiltration and percolation rates have been reported [SCHIFF, 1954, 1955]. Lately, emphasis has been placed on using pits, trenches, and shafts to inject water beneath less pervious soil layers. Special attention is being given to the use of germicides and algaecides.

Contributions have been made to the theoretical and practical aspects of water spreading and soil-water movements based on permeability and hydraulic gradients. Reports on the injection of water in wells to develop pressure mounds to halt the intrusion of ground water are available (J. H. Brown, Los Angeles County Flood Control District, Los Angeles, Calif.).

A procedure has been developed at Seabrook Farms, N. J. for annually disposing of approximately one billion gallons of waste water derived from food processing by means of 'woods irrigation' (Irwin Remson, U. S. Geological Survey, Seabrook, N. J.). The geologic and hydrologic phases of this operation are being investigated by the U. S. Geological Survey. A completed overall study of the disposal area included: the determination of the topography, geology, hydrology, soils, and subsurface conditions. A water-budget study was made taking into account precipitation, water spreading, surface-water runoff, ground-water discharge, evapotranspiration, and changes in ground-water, surface-water, and soil-moisture storage. A statistical solution of the data permitted the determination of transmissibility and specific yield for the area. Water-budget results are being evaluated on the basis of infiltrometer tests, pumping tests, mound-decay studies, basin-drain and other studies. Developments include a method for estimating water losses resulting from capillary rise and later evapotranspiration of water from the water-table aquifers in the spreading area and an equilibrium pumping-test method for determining the specific yield of some of the shallow water-table aquifers in the spreading area. The effect of land-management practices on ground water is considered. The current work is concerned largely with comparisons of soil-moisture instruments, the mechanism of ground-water recharge, the relation between ground water and climatology, and hydrologic relationships in small watersheds. Various publications are listed at the end of this report.

Water spreading is being practiced in a number of areas throughout the country. The infiltration pit at Peoria, Illinois under Max Suter, the Recharge Basins, Mineola, Long Island, N. Y. under W. Fred Welsch, the Rohwer Island spreading canals at Dayton, Ohio under L. C. Huffman and works in other areas are providing valuable information on infiltration under prolonged submergence. Infiltration rates are unusually high and have been approximately doubled in the Peoria infiltration pit by placing a top layer of pea gravel on the pit. An inspection of the surface of the pit shows that the pea gravel contains numerous openings even after a silting period. The pea gravel serves as an effective filter and yet retains sufficient porosity for rapid infiltration. Silt is now removed periodically with a suction-type cleaner.

On Long Island, water first enters an impounding or desilting basin before moving into the recharge basins. Surface crusts that form during water spreading are gently broken with a harrow, and mixing of the material is avoided. Once every several years, when silt has penetrated four to six inches, the top layer of soil is removed and replaced with clean sand. Sand and grits have been used as replacement material lately.

On Rohwer Island, water spreading takes place in canals which meander over the Island. Cleaning methods are similar to those used on the Long Island basins. However, the Mad River supply is quite turbid and cleaning is generally done each fall. Consideration also is being given to the use of material coarser than sand as a top-layer replacement.

Knowledge is developing on spreading sewage effluents [STONE and GARBER, 1951; and UNIVERSITY OF CALIFORNIA, 1953].

Objectives of a California State investigation are: (1) to determine the degree to which the supply to the ground waters is augmented or maintained by artificial recharge; (2) to obtain design criteria and cost data for future use; and (3) to obtain information on operation and maintenance problems (H. O. Banks, California State Division of Water Resources, Sacramento, Calif.).

Artificial recharge to ground water is now an important technique and will become increasingly significant in the future conservation of California's water resources. Execution of the California Water Plan will require the full development and planned utilization of ground-water basins. Artificial recharge will play an important part in the utilization of the major ground-water basins for conservation of local water supplies, and terminal storage of imported waters.

Infiltration, soil moisture, hydraulics--Projects dealing with the hydraulics of water in the root zone are reported, (L. A. Richards, W. R. Gardner, and G. Ogata, Agricultural Research Service, U. S. Salinity Laboratory, Riverside, Calif.). The water-intake rate to the soil is measured during basin irrigation. During this time and afterward, the hydraulic head and hydraulic gradient are measured at various depths in the soil profile. Moisture-content changes in the profile are followed both from information on the moisture retention curve and recording tensiometers and from moisture samplings. Moisture-content changes in the soil are related to the hydraulic gradient, and the hydraulic conductivity of the soil. The depth of the static zone in the profile is followed during the drying out process. Water losses from the soil surface are accurately appraised from salinity measurements that make it possible to integrate upward film flow to the soil surface over any desired time interval.

A study is being made of the hydrology of irrigation, stressing, in particular, soil-moisture measurements, (F. R. Dreibelbis, Agricultural Research Service, Coshocton, Ohio). Information on soil-water depletion rates for different crops at different periods during the growing season is useful in determining the time and amounts of irrigation water to be applied.

The soil-moisture accretion and depletion data, together with precipitation records and results of penetrometer tests were used to predict the trafficability of three soil sites (G. W. Craddock, U. S. Forest Service, Ogden, Utah).

A. F. Pillsbury and S. J. Richards (1954) discuss the effects of various weed control practices in citrus groves and compare the effects of urea and ammonium sulfate on infiltration.

A field experiment is reported on the effect of cultivation with and without the conditioner, vinyl acetate maleic anhydride (G. B. Bodman, University of California, Berkeley, Calif.). A group of plots representing the same six treatments was laid out in each of four peach orchards where prior inspection established the existence of a dense layer, apparently produced by cultivation. Once established, the plots were not cultivated and the traffic was kept off them. Treatments have increased infiltration volumes for comparable times and these have persisted for two complete irrigation seasons. Water-stable aggregation and hydraulic-conductivity measurements have supported those of infiltration. Models are being used to study the wetting patterns for various profile conditions and from simulated irrigation furrows for a wide variety of soil textures and moisture levels [ARONOVICI, 1954, 1955]. Water movements from furrows into the soil are being studied concurrently to establish practical criteria in furrow design and time rate of water application.

Movement of moisture in unsaturated soil as a result of temperature gradients is much greater than has heretofore been thought. Recent studies have indicated that the velocity of movement in response to a given gradient is dependent upon the moisture content of the soil, and is not independent of soil structure and texture. Some of these relationships are being worked out and verified experimentally (S. A. Taylor and L. Cavazza, Utah State Agricultural College, Logan, Utah).

D. B. Krimgold and O. Beenhouwer (Laboratory of Climatology, Johns Hopkins University, Seabrook, N. J., 1954) conclude: (1) There is good reason to believe that infiltration of unfrozen cropland, as defined in this paper, could be expressed quantitatively in terms of measurable soil properties and their variation with depth. (2) Until such time as infiltration can be expressed quantitatively in terms of soil properties that can be measured more accurately and more readily than infiltration itself, rates of infiltration must be determined in the field whenever practicable or possible. (3) General values of infiltration rates assigned on the basis of surface texture only may be so far off that they cannot be used even when general values must be resorted to. (4) An alternative scheme presented is believed to be rational and to correspond more closely to measured values. The soil grouping under each infiltration category and the infiltration values must be considered provisional until they have been verified in the solution of practical problems.

A research project chiefly centers on a large tank of sand upon the surface of which a variety of rainfall intensities may be imposed for any desired length of time (E. C. Childs, University of Cambridge, Cambridge, England). The volume of flow throughout the sand bed may be measured, as also the pressure of the flowing water at different points in the bed from a control room adjacent to the tank room. In this way, flow problems may be solved and numerous boundary effects studied. The electric analogue method is used. The practical application is largely in drainage design but the experimental setup is applicable to many problems of water movement in soils.

New drainage studies designed to measure the effects of water-table draw down and other physical properties related to drainage have been established in the past few years (Don Kirkham, Iowa State College, Ames, Iowa). One of the physical measurements being made is infiltration. The apparatus used is designed so that infiltration and air permeability may be made on the same sample or at the same location.

Conclusions--The Chairman concludes:

It appears that the physical, chemical, and biological studies of soil and water in the laboratory and field are shedding light on hydrology, irrigation, water spreading and drainage. A step in the right direction appears to be the evaluation of small field test units, such as infiltrometers. More work seems desirable to correlate the performance of small units with the performance of large areas.

Hydrologic grouping of soils, long advocated, appears on the way. Permeability ratings being recorded on soil surveys should prove helpful.

It seems as if we are on the threshold of widespread use of information on infiltration which will help solve the many soil and water problems.

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DISCUSSION OF

"ESTIMATING THE MANNING COEFFICIENT FROM AN AVERAGE BED ROUGHNESS IN OPEN CHANNELS"

by M. C. BOYER

[Trans., v. 35, pp. 957-961, 1954]

Steponas Kolupaila (College of Engineering, University of Notre Dame, Notre Dame, Indiana)--Boyer followed an attractive idea: to establish a relationship between the roughness coefficient and velocity distribution, represented by a simple ratio of velocities at 0.2 and 0.8 depth. The empirical Manning equation was confronted with a half-theoretical logarithmic velocity distribution law. A dimensionless ratio $R = v_{0.2}/v_{0.8}$ was plotted against a ratio $n/y^{1/6}$ having a strange dimension, $L^{1/6}$; strange because, opposite to the widespread fallacious judgment, coefficient n has no dimension: the same values are used in both metric and English system and that can be easily checked by conversion factors. The author drew an empirical curve based on seven points only; unfortunately, other measurements were not accompanied by slope leveling. Results presented by Boyer are somewhat discouraging because they depend on system of units.

Writer would like to contribute to this paper something from his own experience. Some 25 years ago he tried to solve a similar problem; then the Lithuanian Hydrometric Bureau had arranged extensive river investigations. The slope had been regularly leveled during each discharge measurement; stream velocities were observed at five points along every vertical across the river.

Data from 34 measurements at eight hydrometric stations on the Nemunas River (Table 2) are taken from earlier publications [KOLUPAILA, 1929, 1930].

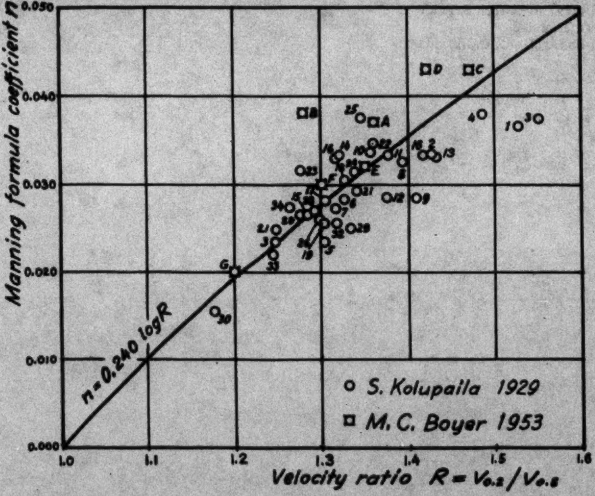

Fig. 3--Relationship of computed Manning coefficient to velocity ratio

Table 2--Results of observations on Nemunas River, Lithuania, 1929

No.	Station	Discharge Q	Average velocity v_m	Average depth y_o	Slope s	Manning coefficient n	Ratio R $v_{0.2}/v_{0.8}$
		m^3/sec	m/sec	m			
1	A	162.5	0.843	2.06	0.000368	0.0368	1.528
2	....	391	1.145	2.73	385	335	1.426
3	....	185.0	0.883	2.03	423	374	1.550
4	....	250	0.957	2.23	454	380	1.485
5	B	229	0.823	2.00	146	233	1.301
6	C	184.9	0.757	1.66	0.000234	0.0284	1.325
7	D	237	0.779	1.59	244	273	1.315
8	E	212	0.752	2.06	231	327	1.391
9	....	176.2	0.785	1.76	234	284	1.408
10	....	889	1.310	4.24	287	339	1.356
11	....	572	1.103	3.43	0.000257	0.0331	1.377
12	....	193.4	0.771	1.88	209	285	1.374
13	....	185.8	0.828	1.70	376	334	1.430
14	....	218	0.816	1.95	307	335	1.320
15	F	214	0.940	2.05	239	265	1.283
16	....	389	1.102	2.38	0.000420	0.0331	1.317
17	....	332	1.129	2.08	377	280	1.304
18	....	272	1.013	1.92	406	307	1.327
19	....	160.7	0.880	1.96	212	259	1.302
20	....	266	1.150	2.03	358	264	1.276
21	....	335	1.142	2.06	0.000420	0.0291	1.340
22	....	610	1.250	3.24	392	347	1.360
23	....	439	1.138	2.58	360	314	1.276
24	....	208	0.887	2.13	281	313	1.337
25	....	248	0.886	1.96	457	378	1.348
26	G	402	0.896	2.23	0.000184	0.0259	1.297
27	....	173.9	0.712	1.28	226	249	1.248
28	....	327	0.860	1.91	224	268	1.290
29	H	304	0.502	2.35	050	249	1.334
30	....	1805	1.090	4.44	038	152	1.177
31	....	1243	0.980	3.97	0.000082	0.0232	1.247
32	....	537	0.674	2.99	069	256	1.317
33	....	697	0.805	3.08	069	219	1.243
34	....	306	0.503	2.43	058	274	1.263

Computed Manning coefficients are represented in Figure 3 against the velocity ratio R, averaged for all verticals across the river. The points by Boyer are marked also (n is put instead of $n/y^{1/6}$); they do not differ much from the Lithuanian data. Some uncertainties in slope leveling and non-uniformity of flow can excuse deviation of several points.

A parabolic law was applied for velocity distribution along a vertical

$$v = v_o(1 - h/H)^x$$

where v is the velocity at a point at the depth h, v_o is the surface velocity, H is the depth of the vertical, x is an exponent, about 1/4 to 1/8.

The ratio for two points $v_{0.2} = 0.8^x\ v_o$ and $v_{0.8} = 0.2^x\ v_o$ is

$$R = v_{0.2}/v_{0.8} = 4^x$$

hence

$$x = \log R/\log 4$$

An empirical relationship has been derived between the Kutter formula coefficient n and the exponent x, as n = 0.150x; the values of n in Manning formula, as compared with the Kutter formula, are in average about four per cent lower; thus the corresponding equation for the Manning n would be n = 0.145x.

Substituting the value of x, a formula follows

$$n = 0.145 \log R/\log 4 = 0.240 \log R$$

The curve is shown on the diagram.

Kenneth N. Phillips (District Engineer, U. S. Geological Survey, Water Resources Branch, Portland, Oregon)--The following points are raised:

(1) In Eq. (1) (Manning's Formula) it is suggested that 1.5 be used rather than 1.486, as the difference would be less than one per cent.

(2) The Manning formula as given in (1) is applicable only to a channel of infinite width, hence (4) has the same limitation. The data plotted in Figure 1, taken from Table 1, are for streams of finite width, some shallow, some deep; some uniform, others not.

(3) It is assumed that the results of Nikuradse's experiments, in which y is given as k/30, apply also to open channels of infinite width. Is such an assumption warranted?

(4) On page 959 it is stated that the Manning coefficient is computed. It should be made clear that the n values were computed directly from measured slopes, areas and discharges (obtained from current-meter measurements at or slightly below crest discharge.)

(5) Since the studies are based on the assumption of a channel of infinite width, it would then be true that the conclusion that n varies as depth to the one-sixth power has the same limitations.

(6) It is believed that the height of roughness k as shown in the photographs would be as hard to determine as the factor n. Probably there would be a wide range of determination of k by different persons.

(7) Does not the density or frequency of trees, grass, and other objects have an effect on n?

C. Toebes (Northland Hydraulic Surveys, Soil Conservation and Rivers Control Council, Ministry of Works, Whangarei, New Zealand)--The author is to be complimented on his worthwhile attempt to find ways and means by which Manning's n can be evaluated for sites for which no detailed data are available.

In Figure 4 the relation between Manning's n and roughness is given. The writer has worked out the theoretical curve for eight detailed current-meter measurements for various stages at one gaging station. The data used include a mean y_0 from three sections, and slope observations on both banks of the river. For calculation of Manning's n the energy gradient was used (see Fig. 4).

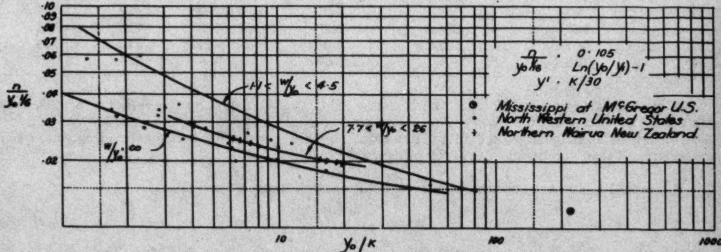

Fig. 4--Relation between Manning coefficient and roughness

The writer's curve, drawn through the data for Northern Wairua, New Zealand data, seems to satisfy the author's proposition and coincides very nearly with the mean curve through the author's observations in natural channels. The bed in the gaging reach consists of a hard uneven rockface and a constant K could be expected. However, the derived values for K vary from 0.77 to 0.34. An estimate of K within these limits can result in an error in the discharge of over 16 pct (computed over the highest discharge value). The fact that roughness in alluvial streams and rivers varies widely with discharge seems to discount the use of formulas which do not take into account the complete bed and side formation in a channel.

To check the ratio $y_1 = k/30$ the writer plotted the estimated median size bedmaterial for about 30 rivers against their computed K values (see Fig. 5). Although a wide scatter is present it seems that the mean line indicates a relationship $y_1 = K/12$.

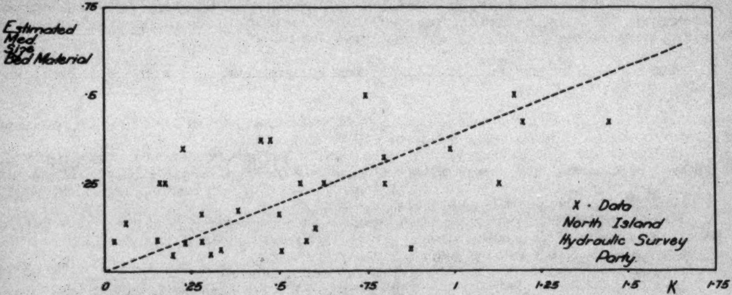

Fig. 5--Relation between median size bed material and height of roughness

Of greater advantage in the definition of Manning's n, the writer sees the relationship of R with $n/y_0^{1/6}$. It definitely could be a useful tool for computing n at gaging stations where measurements of the slope are not possible. The theoretical relationship between R and $n/y_0^{1/6}$ was recomputed and was found to be identical to the author's curve. Following this the ratio $v_{0.2}/v_{0.8}$ was computed for eight current-meter measurements at one gaging station. (Varying from 700 to 6000 cfs) and plotted against their Manning coefficient as derived from field observations (see Fig. 6).

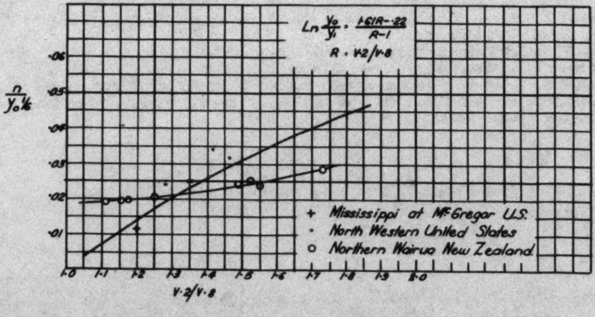

Fig. 6--Relation between Manning coefficient and velocity distribution

The mean line appears to be similar to the author's curve except for a change in position. The close agreement between the points and the mean line is certainly encouraging and warrants further research into the possibility that different lines may be found to exist for different types of rivers.

The author analyzed three medium and high stage discharge measurements for each of the streams listed on Table 1. The writer prefers the treatment of each measurement separately as the n varies with stage quite considerably and by the author's method only a mean n for that particular gaging station is obtained, which, judging by the scatter of observations around the theoretical curve, is already an approximation.

M. C. Boyer (Department of Mechanics and Hydraulics, State University of Iowa, Iowa City, Iowa, Author's closure)--The author is interested in Kolupaila's statement that the Manning coefficient n has no dimension. It has long been his belief that even in the metric system, in which this formula was derived, the coefficient was dimensionless; if dimensional homogeneity is maintained. Kolupaila's curve of relation between the velocity ratio and the Manning coefficient is very interesting. Unfortunately, both his data and that of the author are somewhat limited in range, making curve drawing difficult.

With regard to the points raised by Phillips, the following answers are offered, numbered in order:

(1) There is no particular reason why 1.5 could not be used, as it is so close to the value usually given. The figure 1.486 results simply from a conversion of units.

(2) It is true that the Manning formula as used in this paper is for channels of infinite width. However, most natural streams are much wider than they are deep, so that the effect of the assumption on application of the equation is relatively small. They hydraulic radius of natural channels is generally within five per cent or less of the mean depth.

(3) KEULEGAN [1938] gave an equation for open-channel flow identical to that used in this paper, except that solution of his equation gives $y_1 = k/12$. Using this instead of the factor 30 gives a slightly higher curve (Fig. 1), but does not materially change the results.

(4) That is the manner by which the coefficients were computed.

(5) As pointed out in answer to item 2, it is believed that the width-depth ratio is sufficiently large that this is not a source of serious error.

(6) There undoubtedly could be a considerable range in determinations of k by different observers, though this would be materially less from observations in the field than from photographs, as was done for this paper. However, a 100 pct error in the usual range of y_o/k (from 5 to 10) would produce a corresponding error of less than 25 pct in the value of n as computed. It does not seem likely that a direct observation of n in the field would be more accurate.

(7) Unquestionably these factors have a serious effect on the flow, through the production of excessive resistance, as well as restricting the cross-sectional area. It is not believed that this or any other method will give a precise evaluation of such factors.

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REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

EITEL, WILHELM, Silicate Melt Equilibria, Rutgers University Press, New Brunswick, New Jersey, x + 159 pp., 200 illustrations, 1951, $5.00.

Silicate Melt Equilibria is a translation of the author's 'Die heterogenen Schmelzgleichgewichte silikatischer Mehrstoffsysteme' prepared by J. G. Phillips and T. G. Madgwick with the assistance of a committee (R. B. Sosman, Chairman) of the American Ceramic Society. Professor Eitel revised the translation and added some new material.

The author presents a systematic treatment of phase rule theory with particular emphasis on the application to silicate equilibria. The text is balanced and contains references to the original literature covering the theoretical part of the subject. After some general statements on the phase rule, the author takes up binary systems (34 pages) in which due attention is given to solid solutions (unfortunately called crystalline solutions by the translators), polymorphism, and immiscibility. The same thorough presentation is given for ternary systems (82 pages). The book concludes with the more complex relations of quaternary systems and polynary systems which are admirably and succinctly described (31 pages).

The reviewer feels that a chapter should have been included dealing with the apparatus, methods of study, and the construction of a phase rule diagram from the experimental data.

This book fills a real need in geochemistry and petrology. Student and research scientists alike will be greatly indebted to its author.

GEORGE T. FAUST

EITEL, WILHELM, Thermochemical Methods in Silicate Investigation, Rutgers University Press, New Brunswick, New Jersey, viii + 132 pp., 63 illustrations, 8 tables, 1952, $5,00.

The rapidly growing interest in thermochemical studies amongst students of the silicates has occasioned the preparation of this book. The author is well equipped to write for he was actively engaged in such studies at the Kaiser Wilhelm Institut für Silikatsforschungen at Berlin-Dahlem before World War II. Further, he is well versed in the literature of the subject in all languages.

Geochemists, petrologists, mineralogists, and geologists who are familiar with the basic concepts of physical chemistry will find this to be a very readable and comprehensible introduction to the subject. Following an introductory chapter on heats of formation and reactions, Eitel presents brief descriptions, liberally illustrated, and discussions of the various types of calorimeters for the determinations of heats of reaction. This is followed by a chapter on the equations and calculations involved in determining: (a) Heat capacity as a function of the temperature; (b) Kirchoff equation; (c) Heats of inversion directly determined, metastable phases; (d) Calculation of the free energy changes. Methods for determining reaction affinities are next described. The succeeding chapter entitled Examples for the Calculation of Free Energy Changes and Affinities will be of particular interest, for Eitel here presents a discussion of the $\Delta H - \Delta F$ diagrams for cristobalite-quartz, quartz-silica glass, kyanite-sillimanite, wollastonite $\rightleftharpoons$ pseudowollastonite. In addition, he presents thermochemical calculations and a discussion of the system $CaCO_3 + SiO_2 \rightleftharpoons CO_2 + CaSiO_3$ of considerable interest in the petrology of metamorphic rocks. The final chapter of the book treats very briefly: (a) The possibility of anomalies at low temperatures; (b) The statistical meaning of entropy. The two appendices add very much to the value of the book. In Appendix I, Eitel gives two examples of the treatment of experimental data, (1) the evaluation of the heat of solution of tricalcium silicate, and (2) the heat of solution of the mineral sillimanite. Appendix II contains tables of heats of formation, data for changes in state, heat capacity equations, and entropies at 298.16°K.

Eitel has adopted the thermodynamic symbolism in wide use in the United States. The reader should pay particular attention to the convention on signs: paragraph 2; notes 1 and 3 following paragraph 13; and note 92 following paragraph 65.

This book should make many friends.

GEORGE T. FAUST

PASK, JOSEPH A., and MORT D. TURNER (Ed.), Proceedings of the First National Conference on Clays and Clay Technology, a Symposium, Clays and Clay Technology, State of California, Department of Natural Resources, Division of Mines, San Francisco, California, Bull. 169, 326 pp., many illustrations, 1955, $4.50.

The First National Conference on Clays and Clay Technology was held at Berkeley, California in 1952. Its purpose was to summarize our knowledge of the chemical, physical, and mineralogical properties of clay, and their applications to the broad field of clay technology. This book is a record of that conference.

It consists of seven parts: Part I - Geology and Mineralogy of Clays; Part II - Properties of Clays; Part III - Methods of Identifying Clays and the Interpretations of Results; Part IV - Clay Technology in Soil Science; Part V - Clay Technology in Soil Mechanics; Part VI - Clay Technology in Ceramics; Part VII - Clay Technology in the Petroleum Industry. The subjects listed above are discussed in 25 papers.

This book is an outstanding contribution to our knowledge of the properties of the clay minerals and their behavior in simple and complex natural and artificial systems. For those who are interested in the clay minerals, it will prove indispensable. The editors and the California State Division of Mines who published this work are to be congratulated.

GEORGE T. FAUST

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NOTES AND PERSONALIA

NOTES

International Geophysical Year--Delegates from thirty nations participating in the International Geophysical Year program met in Brussels, September 8-14, 1955 at the third assembly of the Comité Spécial de l'Année Géophysique Internationale (CSAGI), established by the International Council of Scientific Unions. The United States delegation, headed by Joseph Kaplan, Chairman, and Hugh Odishaw, Secretary, took part in integrating the technical efforts of the participating nations, now totaling 40. The principal tasks before the assembly were reviews and coordination of the national programs, establishment of criteria for data interchange, and the development of initial plans for data publication. Substantial progress was made in the deliberations of working groups which were set up in the various IGY fields of interest, and the results met with unanimous approval in the final plenary sessions. A preliminary assessment of the outcome of the assembly indicates that the IGY Program has developed beyond the initial plans arrived at last year at the CSAGI-Rome Meeting, primarily because several new participants have entered the program. It appears now that almost complete coverage of the Earth's surface will be achieved during IGY, including such large geographical areas as the territory of the USSR, the Antarctic continent, and the Pacific Ocean.

The following bibliographical items concerning the International Geophysical Year will provide quite full information on plans developed up to the present time.

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Meeting of the International Council of Scientific Unions held in Oslo--A General assembly of ICSU was held in Oslo, Norway, August 9-12, 1955. The delegation of nine from the United States consisted of Lloyd V. Berkner (Chairman), W. W. Atwood, Jr., Robert B. Brode, Detlev W. Bronk, Walter H. Bucher, Jason J. Nassau, Walter M. Rudolph, C. E. Sunderlin, and Paul A. Weiss. The following officers were elected: Lloyd V. Berkner, President; K. S. Krishnan (India), and P. Lejay (France), Vice Presidents; A. V. Hill (United Kingdom), Secretary General; E. Herbays (Belgium), Treasurer; with V. A. Engelhardt (USSR) and A. Stoll (Switzerland) as elected members of the Bureau, and B. Lindblad as retiring President. W. A. Noyes, Jr., of the United States was not a candidate for reelection as Treasurer.

Conference on the Antarctic held in Paris--On July 6-10, 1955, a conference of the representatives of 12 nations that are planning to maintain Antarctic stations during the International Geophysical Year, 1957-1958, was convened to integrate plans for the work in the Antarctic. It is planned that at least 42 stations will be established in the Antarctic and sub-Antarctic, 20 of which will be on the Antarctic Continent, including six established by the United States. The United States accepted responsibility for the handling of the Weather Central in the Antarctic, all reports being transmitted from the local stations to the central station to be established at Little America. Various working arrangements were detailed. Representing the United States were Laurence M. Gould (Chairman), Hugh Odishaw (Secretary), A. H. Shapley, Harry Wexler, George Dufek, Paul A. Siple, and J. Wallace Joyce.

Graduate assistantships in Meteorology at Florida State University--The Department of Meteorology, Florida State University, announces the availability of Graduate Assistantships for the academic year 1956-1957. Any candidate for the M. S. or Ph. D. degree in Meteorology and Climatology is eligible to apply. No previous meteorological education is necessary, but the applicant's undergraduate education must have included at least one year of calculus and one year of university-level physics.

A Graduate Assistantship carries a stipend of $1680 per calendar year for students holding a bachelor's degree, and $1980 for students holding a master's degree in meteorology. For application forms and other details, write to Werner A. Baum, Head, Department of Meteorology, Florida State University, Tallahassee, Florida. Applications should be filed before April 15, 1956.

New radio-meteorographic stations in the Norwegian Arctic--The Meteorological Institute of Norway has announced the expansion of work in the Arctic by the establishment of a new station at Isfjord and enlargement of the station at Bear Island, both in Spitzbergen, in a general plan to improve weather forecasting in the region.

New Journal on Electronics--Volume 1, Number 1 of the Journal of Electronics is being published in England and is available in this country through the Academic Press. The first number issued in July, including a foreward by Sir Edward Appleton in which he notes that the Journal will be devoted to the free and almost free electrons, that is, the description of the behavior of electrons in states where their binding energy is low. It is noted that this is a descendant of a long-established scientific journal, The Philosophical Magazine. J. Thomson of the Royal Naval Scientific Service will serve as Editor and N. F. Mott as consultant editor. It is anticipated that Volume 1, issued in six parts, will contain about 600 pages. The price is $15.40 for the volume, with single issues at $2.80.

Fall Meeting of URSI to be held in Gainesville, Florida, December 15-17, 1955--The Fall Meeting of the United States National Committee of URSI will be held at the University of Florida at Gainesville, December 15-17, 1955. Sessions will be held by the following Commissions: Radio and Troposphere, Ionospheric Radio, Radio Noise of Terrestrial Origin, and Radio Astronomy. The Secretary of the U. S. National Committee is John P. Hagen, Code 7100, Naval Research Laboratory, Washington 25, D. C.

New Argentinean Publication--A new publication called Atlas, the Official Organ of the Institute of Military Geography of Argentina, was published in April, 1954. Number Two of the series, the only other one to arrive here, was published in December, 1954.

New Subminiature Gyro Compass--A small gyro compass, less than two per cent of the size of its large predecessors and small enough to be carried in one hand, but which is accurate and rugged, has been developed by the American Bosch Arma Corporation for the Corps of Engineers Research and Development laboratories of the U. S. Army. This recently successfully passed rigorous tests in a helicopter.

United Nations Conference on Peaceful Uses of Atomic Energy--This Conference was held in Geneva, Switzerland, August 8-20, 1955, and received much attention and acclaim in the Press and on the radio. Among those in attendance from the United States were Harrison Brown of the California Institute of Technology, Harold C. Urey of the University of Chicago, and Detlev W. Bronk, President of the National Academy of Sciences.

PERSONALIA

Joseph W. Berg, formerly Professor of Geophysics at the University of Tulsa, has been designated Assistant Professor in the Department of Geophysics at the University of Utah.

Lloyd V. Berkner, President of Associated Universities which operates the Brookhaven National Laboratory and Chairman of AGU's Committee on International Participation, will be a principal speaker at the Fifth National Conference of the United States National Commission for UNESCO to be held in Cincinnati, Ohio, November 3-5, 1955.

Arthur Bevan, Principal Geologist of the Illinois State Geological Survey, has retired and will devote his energies to studies of the Appalachian Mountains of west-central Virginia. Before he took up duties with the Illinois Geological Survey, he had served as State Geologist of Virginia for 18 years.

Marion R. Carstens of the School of Civil Engineering of the Georgia Institute of Technology has been given the J. C. Stevens Award of the American Society of Civil Engineers for his discussion of the paper entitled Mechanics of Manifold Flow.

Leo O. Colbert, Director of the Washington Office of the Arctic Institute of North America and past Director of the U. S. Coast and Geodetic Survey, has been elected to honorary membership in the American Society of Civil Engineers.

George B. Cressey, Maxwell Professor of Geography at Syracuse University, is devoting the current year to research on water problems in southwest Asia, with headquarters at Baghdad, Iraq.

Alfred B. Focke has been named Director of the Marine Physical Laboratory of the University of California in La Jolla.

Paul D. Foote of Gulf Research and Development Company has been designated as a member of a Special Commission on Rubber Research by the National Science Foundation.

Gordon Gunter is leaving his work as Director of the University of Texas Institute of Marine Science and has accepted an appointment as Director of the Gulf Coast Research Laboratory at Ocean Springs, Mississippi.

Lloyd L. Harrold, Director, Coshocton (Ohio) Hydrologic Experiment Station of the U. S. Department of Agriculture, was recently awarded the Hugh H. Bennett Gold Medal of the Friends of the Land for his contributions to the cause of soil and water conservation.

William T. Holser has left his work with Battelle Memorial Institute to accept an appointment as Assistant Research Geochemist with the Institute of Geophysics of the University of California.

Wesley W. Horner of Horner and Shifrin, consulting engineers, has been given the Gold Achievement Award Medal of the Engineers' Club of St. Louis.

Walter L. Huber of Huber and Knapik, Engineers, of San Francisco, has been awarded an honorary doctorate by the University of California.

Paul H. Jones, District Geologist in charge of ground-water investigations for the U. S. Geological Survey in Pennsylvania, is now on a two-year assignment to the International Cooperation Administration and is serving as technical advisor to the Geological Survey of India on their Exploratory Tubewells Project.

Joseph Kaplan, Professor of Physics at the University of California at Los Angeles, devoting much of his time to the work of the U. S. National Committee on the International Geophysical Year, of which he is the Chairman.

H. Arnold Karo, Rear Admiral, U. S. Coast and Geodetic Survey, has been designated as the new Director to succeed R. F. A. Studds who has retired.

Penn P. Livingston has retired as Hydraulic Engineer for the Ground-Water Division of the U. S. Geological Survey after more than 32 years of service. He has taken up duties as Senior Hydrologist for the Ralph M. Parsons Co. of Los Angeles on exploratory test drilling for irrigation water in India.

John S. McNown of the Department of Engineering Mechanics of the University of Michigan has been awarded the J. James R. Croes Medal of the American Society of Civil Engineers for his paper entitled Mechanics of Manifold Flow.

Hugh Odishaw, formerly Assistant to the Director of the National Bureau of Standards, is now on the staff of the National Academy of Sciences in Washington as Executive Secretary of the United States National Committee for the International Geophysical Year.

Stanley Ruttenberg, formerly with the Institute of Geophysics of the University of California, Los Angeles, has joined the Secretariat of the United States National Committee for the International Geophysical Year as Assistant Program Officer.

G. F. Schilling, of the Institute of Geophysics, University of California, has been named Program Officer of the United States National Committee for the International Geophysical Year of the National Academy of Sciences, Washington, D. C.

William M. Smith of the University of California, Los Angeles has been appointed to the Secretariat of the United States National Committee for the International Geophysical Year and will take over the duties of Assistant to the Program Officer.

Robert Stoneley, Professor of Theoretical Geophysics at Cambridge University, Fellow and Director of Studies in Mathematics in Pembroke College of the University, and Past President of the Association of Seismology, IUGG, is now visiting Professor of Geophysics at American University. He is working also on problems in theoretical geophysics at the National Bureau of Standards. The research arrangement is under a contract between the Office of Naval Research and American University.

H. W. Thoms, Office Geologist for the Creole Petroleum Corporation, recently retired and has established a consulting office in Caracas, Venezuela.

William F. Uhl, President of Charles T. Main, Inc., consulting engineers, has been named a Fellow of the American Institute of Electrical Engineers 'for his contributions to the development and design of hydroelectric plants.'

Robert B. Campbell, Consulting Geologist, died in New Jersey, while away from his home in Fort Myers, Florida, on August 16, 1955, at the age of 63. He was born in Philadelphia and received his baccalaureate degree from Springfield College (Massachusetts), subsequently studying at the University of Nancy, in France, and the University of Chicago. He served as Geologist for the Humble Oil and Refining Company from 1919 to 1926, and had been in consulting work since that time in West Texas, Western Canada, and Florida. He was President of the Peninsular Oil and Refining Company from 1934 to 1942. He had been a member of the American Geophysical Union since 1944.

Albert Edward Cummings, Director of Research and a Director of the Raymond Concrete Pile Company, died July 20 at the age of 61. He was born in St. Louis, Missouri, took his baccalaureate degree from the University of Wisconsin in 1915, and devoted almost his entire career to service with the Raymond Concrete Pile Company, beginning in March, 1916 as a field clerk. He progressed rapidly in the Company and in 1920 was named District Manager with headquarters in Chicago. Since 1944 he had served as Director of Research, and in 1947 was elected a Director of the Company. His work in the field of soils mechanics is well known. He was very active in the International Society of Soil Mechanics and Foundation Engineering and was a representative from the United States at the last International Conference on Soil Mechanics and Foundation Engineering held in Switzerland, August 15-17, 1953. He had been a member of AGU since 1947.

Lafayette Brown Herring, Consulting Geologist of Houston, Texas, died suddenly on March 3, 1955. He was born at Fulton, Kentucky in 1900 and took his baccalaureate degree from the University of Kentucky in 1922. He began his professional career as a petroleum geologist for the Marland Oil Company (now Continental), with which organization he served until 1929. For five years he served as a geologist with McElreath and Suggett in Fort Worth, and in 1934 established his own office as a petroleum geologist and engineer. In 1946 he became Vice President and Manager of the Oil and Gas Division of the Second National Bank of Houston, and at the time of his death was a member of the Board of Directors of the Southern Production Company and associated Oil and Gas Company. He had been a member of AGU since 1947.

William A. James, Advertising Representative for the Transactions, American Geophysical Union, died in New Haven, Connecticut, August 2, 1955, at the age of 62. He was born at Sandy, Utah and took his baccalaureate degree at Yale University. He was a prominent Yale alumnus who had devoted most of his career to the managing of various publications, notably those relating to Yale University and alumni affairs. At the time of his death he was serving as Advertising Representative for the Yale Review, the American Scholar, and the American Scientist, and only in the early summer had undertaken similar work for the Transactions of the American Geophysical Union.

UNION, SECTION, AND COMMITTEE ACTIVITIES

CONFERENCE ON THE PHYSICS OF CLOUD AND PRECIPITATION PARTICLES ARRANGED BY COMMITTEE ON CLOUD PHYSICS, AGU

A meeting of the Committee on Cloud Physics of the Section of Meteorology, AGU, Helmut Weickmann, Chairman, was held at Woods Hole Oceanographic Institution, September 7-10, 1955. This Conference was arranged under contract between the National Academy of Sciences and the Air Force Cambridge Research Center with funds supplied by the Air Force and the Office of Naval Research. A program of about 45 papers was presented over the $3\frac{1}{2}$-day conference period, with about 75 active workers in the field of Cloud Physics taking part. The Conference served to bring these active workers together once more to present their latest findings in this very active scientific field. Plans for the publication of papers and discussions of the Conference will be announced subsequently.

ACTIVITIES OF THE PACIFIC NORTHWEST REGIONAL GROUP

C. C. McDonald, Chairman of the Regional Committee, resigned because of his transfer to Washington, D. C. In his place, the Committee selected Milton S. Sachs. Others on the Committee are V. P. Schermerhorn (Secretary-Treasurer), C. A. Barnes, Peter B. Boyer, T. H. Campbell, Fred Natella, and Wilbur D. Simons. A Nominating Committee consisting of R. A. Work (Chairman), K. E. Anderson, Phil E. Church, N. A. Leupold, and A. M. Piper has been designated to name the official nominees for the Committee for the triennium 1956-1959. Last spring, the Committee organized and sponsored a course of seminar lectures in hydrology under the auspices of Oregon State College. Lectures by representatives of the several Federal agencies in Portland that deal in one aspect or another of hydrology were included in the course. Plans are under way for monthly luncheon meetings in Portland, and the possibilities of such meetings are being explored in other centers, also.

ACTIVITIES OF THE MID-PACIFIC REGIONAL GROUP

The Geophysical Society of Hawaii, serving as the Mid-Pacific Regional group of the American Geophysical Union and the local branch of the American Meteorological Society, recently elected officers for the ensuing year as follows: President, Joel B. Cox; Vice President, H. Dean Parry; Secretary-Treasurer, Laurence E. Eber; and Councilor (two years), Thomas S. Austin. On the Council also will serve William R. Crawford, elected a year ago, and John F. Mink, Retiring President.

Secretary Eber has recently written a three-page history of the Society that traces its beginnings back to 1931, although this became officially our Mid-Pacific Regional group only early in 1955. Since 1952, the group has been very active, and in the intervening period has held some 27 meetings, mostly evening lectures, but with an occasional seminar. Through the 1953-1954 season, a series of sessions were held with moderator, principal speaker, and discussants. These served as a great stimulus to the group. As noted under Special Announcements, their first three-day meeting will be held starting November 15, 1955. Anyone interested in getting into touch with the group should write to the Secretary-Treasurer at P. O. Box 3166, Honolulu 2, Hawaii.

SPECIAL ANNOUNCEMENTS

AGU Elections in 1956-- The current triennium of the American Geophysical Union ends June 30, 1956, and the terms of all incumbent elected officers expire at that time. Elections will be held early in 1953 to elect officers of the Union and the Sections for the triennium ending June 30, 1959.

Election procedures were established by the Executive Committee of the Union and by the Sections in 1946 [see Trans., v. 27, pp. 910-914, 1946], modified somewhat for Seismology and Hydrology in 1949 [see Trans., v. 30, p. 927, 1949], and in 1952 for the Section of Geodesy (one nominee for each office is now permitted instead of two). The following is the time-table for the election.

October 15, 1955--Reports of Committees on Nominations of Union and Section officers to be filed, and, in connection with the Union Nominating Committee, the Executive Committee will perform its functions under item 3 of the procedure established in 1946. The names of 'official nominees' of the Union and the Sections will be published in the December, 1952, issue of the Transactions.

February 10, 1956--All nominations by petition for Union and Section officers must be in the office of AGU, including written consent of the petition nominees, by February 10, 1956.

March 1, 1956--Ballots carrying the names of officials and petition nominees for officers of the Union and the Sections will be mailed to members not later than March 1, 1956. A brief biographical sketch relating to each nominee will accompany, but not be a part of, the ballot.

March 31, 1956--Balloting will close March 31, 1956. Ballots must be postmarked not later than that date, and be received not later than April 4, 1956, in order to be counted.

April 30 - May 2, 1956--Announcement of the results of the election will be made at the Business Sessions of the Union and the Sections at the Annual Meeting, April 30 - May 2, 1956. Results will also be published in the June, 1956, issue of the Transactions.

Change in payment necessary to secure life membership--By Law 2 [Transactions, June, 1955, p. 567] state 'Any Member or Associate, on payment of not less than $100 at any time, the amount to be fixed by the Executive Committee of the Union, shall be relieved of further payment of dues.' Notice is hereby given that the Executive Committee has set the amount beginning January 1, 1956, at $150. Annual dues will be $8 in 1956, and Transactions will be in a new format, printed by letter press.

Mid-Pacific Regional Meeting to be held in Honolulu starting November 15, 1955--The program for this meeting is substantially complete. Scientific papers will be read at sessions on November 15-17, with the themes of the sessions bearing on Weather Forecasting, Tropical Meteorology, Cloud Physics, Agricultural Meteorology, Oceanography, Hydrology, Volcanology, and Seismology. There will also be a Symposium on Weather Reconnaissance during the International Geophysical Year, 1957-58. A total of 18 sessions are scheduled. This group, called the Geophysical Society of Hawaii, is the Mid-Pacific Regional organization of the American Geophysical Union and the local branch of the American Meteorological Society. Persons interested in the meeting should get into touch with the Secretary-Treasurer, Laurence E. Eber of the Pineapple Research Institute, Honolulu.

Pacific Northwest Regional Meeting to be held in Portland, Oregon, November 17-18, 1955--The program for this meeting is substantially complete. The meeting will start with a business meeting on the morning of November 17, with a scientific session in the afternoon and another the next morning. On the evening of November 17, a dinner will be held at which the speaker will be Brigadier General L. H. Foote, the North Pacific Division Engineer of the Corps of Engineers. The general theme of the meeting will be on the meteorologic and hydrologic problems of the development and management of the water resources of the Pacific Northwest. Interested persons should write to the Chairman, Milton S. Sachs, P. O. Box 3537, Portland 8, Ore., or the Secretary-Treasurer, V. P. Schermerhorn, 320 Custom House, Portland 9, Ore.

Meeting in Atlanta, Georgia, December 27-29, 1955--The *ad hoc* Southeastern Regional Committee under the chairmanship of Werner A. Baum has arranged a general scientific session for the afternoon of December 28, to be held, according to the present schedule, in Committee Room 1 of the Municipal Auditorium, jointly with the American Meteorological Society. For details, get into touch with Chairman Baum at the Department of Meteorology, Florida State University at Tallahassee.

A Symposium on the United States Participation in the International Geophysical Year, 1957-58, will be held in the same room on the mornings of December 27, 28, and 29. This will be jointly sponsored by the AGU with the American Association for the Advancement of Science, the U. S. National Committee for IGY, and the National Science Foundation, and is being arranged by a Committee of which Joseph Kaplan is the Chairman. Papers will be presented on the scientific programs planned for the fields of Aurora and Airglow, Cosmic Rays, Geomagnetism, Glaciology, Gravity, Ionosphere, Longitude and Latitude, Meteorology, Oceanography, Rockets, Satellites, Seismology, and Solar Activity. The speakers will include Lloyd V. Berkner, C. T. Elvey, W. O. Field, Jr., L. M. Gould, E. O. Hulburt, Joseph Kaplan, James B. Macelwane, H. E. Newell, Jr., M. G. Morgan, R. R. Revelle, J. A. Van Allen, Harry Wexler, and George P. Woollard. The Symposium will afford an unusual opportunity to present a review of our knowledge in these fields to the general scientific public, and to present the potential contributions of the IGY program to an extension and enhancement of this knowledge.

These meetings will be a part of the 122nd Meeting of the American Association for the Advancement of Science which extends from December 26-31, as indicated in previous Special Announcements.

Pacific Southwest Regional Meeting to be held at University of California in Los Angeles, January 26-27, 1956--The Regional Committee has designated Arthur F. Pillsbury, Professor of Irrigation and Soils at the University as the General Chairman and as Program Chairman for the Section of Hydrology, James G. Edinger, Professor of Meteorology at the University as Program Chairman for the Section of Meteorology. Titles and abstracts of papers for the program should be sent to one or the other as appropriate. Other Sections are invited to participate, and further appointments will be made as is appropriate. It is now planned that a general session will be held on the morning of January 26, and that that afternoon and the next day each Section will have its own sessions. The Chairman of the Regional Committee is Martin R. Huberty (Professor of Irrigation, University of California, 59 Physics-Biology Building, Los Angeles 24, California) and the Secretary is R. Corday Counts, Jr., (1472 Cortez Avenue, Burlingame, California).

Thirty-Seventh Annual Meeting to be held in Washington, D. C., April 30-May 2, 1956, with special Symposium on the Antarctic on April 26-27, 1956--As announced in the August issue of the *Transactions*, the Thirty-Seventh Annual Meeting will be held in Washington, D. C., April 30-May 2 (Monday to Wednesday), 1956. Plans for the meeting are under way, and it is anticipated that all Sections will have sessions. In addition, AGU is co-sponsoring, with the United States National Committee for the International Geophysical Year, 1957-58, and the National Science Foundation, a two-day Symposium on the Antarctic to be held on the Thursday and Friday of the previous week, April 26-27. Place this information on your calendar and make plans to come.

This announcement serves also as an invitation for members and others to send word of plans for papers to be presented during the meeting proper (excluding the Symposium). Titles of papers with three copies of the abstract should be sent as soon as possible, and not later than March 5, 1956, with advice concerning the time required (most papers are allowed from ten to 20 minutes) and the projection equipment needed. Send this word to the office of AGU at 1530 P Street, N. W., Washington 5, D. C., or to the Secretary or Program Chairman of the appropriate Section, as follows:

Geodesy	Frank L. Culley	U. S. Coast and Geodetic Survey Washington 25, D. C.
	or	
	Donald A. Rice (Program Chairman)	U. S. Coast and Geodetic Survey Washington 25, D. C.
Seismology	James A. Peoples, Jr.	39 Edgewater Drive Waltham 54, Mass.
Meteorology	Woodrow C. Jacobs	4302 Kentbury Drive Bethesda 14, Md.
Terrestrial Magnetism and Electricity	Leroy R. Alldredge	3133 Jennings Road Kensington, Md.
Oceanography	Donald W. Pritchard	Chesapeake Bay Institute RFD 2, Box 426a Annapolis, Md.
Volcanology, Geochemistry, and Petrology	Felix Chayes	Geophysical Laboratory 2801 Upton Street, N. W. Washington 8, D. C.
	or	
	George S. Switzer (Program Chairman)	U. S. National Museum Washington 25, D. C.
Hydrology	Harry F. Blaney	1509 P. O. and Court House Bldg. U. S. Dept. of Agriculture Los Angeles, Calif.
	or	
	Ralph N. Wilson (Program Chairman)	3322 Stanford Drive University Hills Hyattsville, Md.
Tectonophysics	James T. Wilson	Department of Geology University of Michigan Ann Arbor, Mich.

As the Section Secretaries reserve the right to close filled programs in advance of the date indicated, it is desirable that word concerning papers be sent in early. It is the plan to publish abstracts in the program. Remember that an abstract is an opportunity to bring the important results of your work to all who see the program. It must be concise, but comprehensive, and not exceed 200 words. Longer abstracts will be reduced to 200 words or omitted at the editor's discretion. Complete manuscripts of papers are not necessary, but are desired, and should be forwarded to the office of the Union by April 15, 1956. Indicate whether the paper is being submitted for the program only or also for consideration for publication in the Transactions. (Papers for publication only are also welcome for consideration for the Transactions.)

If a paper is written in collaboration, please indicate by whom it will be presented. Arrangements can usually be made with the Section Secretary or Program Chairman for presentation of papers by authors who are unable to attend, but papers to be presented by title only are not included in the program.

The Chairman of the Committee on Meetings (John N. Adkins, 11619 College View Drive, Wheaton, Md.) invites suggestions and comments that will be helpful in planning this meeting. Especially invited are comments relating to papers and symposia bearing on more than one Section.

Make hotel or room reservations directly with the hotel of your choice at an early date. If you fail on the first attempt, bear in mind that advance booking not taken up are canceled two weeks in advance and that a follow-up request in mid-April may bring the desired response. We are making block booking at two or three hotels again, an announcement concerning which will appear in the SPECIAL ANNOUNCEMENTS of the December 1955 issue of the Transactions.

John N. Adkins, Chairman
Committee on Meetings

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TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

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VERTICAL EXTRAPOLATION OF GEOMAGNETIC FIELD COMPONENTS

Alfred Zmuda and Lowell McClung

Abstract--In the region external to sources of magnetism, both the divergence and the curl of the magnetic intensity are zero. From the corresponding analytic expressions, the derivatives in the vertical direction of each field component are obtained in terms of the values of the components on a surface surrounding the sources. A Taylor series is formed with these derivatives and then used to continue, either upward or downward, the respective components. The rapidity of the convergence depends on the complexity of the surface field and on the distance of the computed point from the surface.

Introduction--If the Earth's magnetic field were known for all points on a sphere enveloping the sources of the field, that at all exterior points could be calculated rigorously. From less complete data, an approximation to the external field is obtainable. One approach to this problem is based on the analysis by spherical harmonics of the surface data, as for example the one conducted by VESTINE and Others [1947]. In addition to the main features so depicted, however, the measurements show a pattern of irregularity or fine structure, the so-called anomaly field, which is far too intricate to be fitted by spherical harmonics of any practicable order of fineness. Consequently, the field at any given point aloft is by such an analysis left undefined to the extent of the contribution of the anomaly field. This contribution would ordinarily arise chiefly from irregularities occurring in the local region beneath the point in question, and it may have a pronounced effect, particularly at heights not far removed from the surface.

The effects of magnetic anomaly at various altitudes have been investigated in several ways, both by calculation and by model studies, though usually with limiting assumptions of one kind or another. Some of the studies in the literature are cited in papers by ZIETZ and HENDERSON [1951, 1954] who used assumptions of a plane Earth and a constant vector for the undisturbed portion of the field. In the present paper we describe a method by which the main field, including the anomaly, may be extrapolated to moderate altitudes above or below a surface where component data are available. In this method each component is separately continued by a Taylor series in which the vertical derivatives are computed from values of the components at the surface.

Some properties of the geomagnetic field--In the region external to the magnetic sources producing the Earth's field, using polar coordinates r, θ, ϕ with origin at the Earth's center, the intensity of the magnetic force $\vec{F}$ satisfies the relation

$$\vec{F} = -\operatorname{grad} V = -[\vec{i}_1\, \partial/\partial r + \vec{i}_2\, \partial/r\, \partial\theta + \vec{i}_3\, \partial/r \sin\theta\, \partial\phi]\, V \quad \ldots\ldots\ldots \quad (1)$$

where $\vec{i}_1$, $\vec{i}_2$, $\vec{i}_3$ are unit vectors in the directions of increasing r, θ, ϕ, respectively. Also

$$\operatorname{Curl} \vec{F} = (\vec{i}_1/r\sin\theta)\,[\partial(Y\sin\theta)/\partial\theta - \partial X_n/\partial\phi] + (\vec{i}_2/r)\,[\partial Z_n/\sin\theta\, \partial\phi - \partial(rY)/\partial r]$$
$$+ (\vec{i}_3/r)\,[\partial(rX_n)/\partial r - \partial Z_n/\partial\theta] = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

and

$$\operatorname{div} \vec{F} = \partial Z_n/\partial r + 2Z_n/r + \partial X_n/r\, \partial\theta + X_n/r\tan\theta + \partial Y/r\sin\theta\, \partial\phi = 0 \quad \ldots\ldots \quad (3)$$

where Z_n, X_n and Y are the field components in the upward, southward, and eastward directions, respectively. Note that X_n and Z_n have signs contrary to those of the conventional geomagnetic components where the northward and downward directions are considered positive. The choice of the latter directions would have been awkward here since they do not correspond to increasing θ and r.

The magnetic potential V satisfies Laplace's equation

$$\nabla^2 V = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where the operator ∇^2 is given by

$$(1/r^2)(\partial/\partial r)(r^2\,\partial/\partial r) + (\partial/r^2 \sin\theta\,\partial\theta)(\sin\theta\,\partial/\partial\theta) + \partial^2/r^2 \sin^2\theta\,\partial\phi^2 \ldots (5)$$

The problem of determining V uniquely, thereby determining F through (1), in regions outside a surface surrounding the sources of magnetism, is one of finding a solution of (4) which reduces to known values on the boundary, the well-known Dirichlet or first-boundary-value problem of mathematical physics.

The solution of Laplace's equation is expressible as a series of spherical harmonics of the form

$$V = a \sum_{n=1}^{\infty} \sum_{m=0}^{n} P_n^m (\cos\theta)(a/r)^{n+1} \left[A_n^m \cos m\phi + B_n^m \sin m\phi \right] \ldots\ldots\ldots (6)$$

where $P_n^m(\cos\theta)$ is an associated Legendre function, and A_n^m and B_n^m are coefficients evaluated from data on the spherical surface $r=a$, usually the surface of the Earth.

From (1) and (6) the components of the field may be written as

$$X_n = -\sum_{n=1}^{\infty} \sum_{m=0}^{n} (a/r)^{n+2} \left(\partial P_n^m(\cos\theta)/\partial\theta\right) \left[A_n^m \cos m\phi + B_n^m \sin m\phi \right] \ldots\ldots (7)$$

$$Y = -\sum_{n=1}^{\infty} \sum_{m=0}^{n} (a/r)^{n+2} P_n^m(\cos\theta)(\partial/\sin\theta\,\partial\phi) \left[A_n^m \cos m\phi + B_n^m \sin m\phi \right] \ldots (8)$$

and

$$Z_n = \sum_{n=1}^{\infty} \sum_{m=0}^{n} (n+1)(a/r)^{n+2} P_n^m(\cos\theta) \left[A_n^m \cos m\phi + B_n^m \sin m\phi \right] \ldots\ldots\ldots (9)$$

From an analysis of world-wide magnetic measurements, VESTINE and Others [1947] have evaluated 48 coefficients of the series in (6), up to $n = m = 6$, for best fit by least squares. Using these coefficients, the main structure of the Earth's field may be calculated for any height over any part of the Earth's surface.

Extrapolation of components--In an alternative method of upward continuation of the field, the value of each component at a height h above a spherical surface $r = a$ may be determined from the Taylor series expansion for each component. This expansion is permissible since the components are analytic functions in the regions external to the sources of magnetism. The respective series are

$$X_n(h) = X_{n(r=a)} + h(\partial X_n/\partial r)_{r=a} + (h^2/2!)(\partial^2 X_n/\partial r^2)_{r=a} + \ldots \quad \ldots (10)$$

$$Y(h) = Y_{r=a} + h(\partial Y/\partial r)_{r=a} + (h^2/2!)(\partial^2 Y/\partial r^2)_{r=a} + \ldots \quad \ldots\ldots\ldots (11)$$

$$Z_n(h) = Z_{n(r=a)} + h(\partial Z_n/\partial r)_{r=a} + (h^2/2!)(\partial^2 Z_n/\partial r^2)_{r=a} + \ldots \quad \ldots (12)$$

All vertical partial derivatives, that is, derivatives with respect to r, are obtained from the values of the components and their variations on the surface so that single-level measurements suffice for an upward continuation. The first partial derivatives with respect to r are given by the equations

$$\partial X_n/\partial r = (1/r)\left[\partial Z_n/\partial\theta - X_n\right] \ldots\ldots\ldots\ldots (13)$$

$$\partial Y/\partial r = (1/r)\left[\partial Z_n/\sin\theta\,\partial\phi - Y\right] \ldots\ldots\ldots\ldots (14)$$

which are obtained from the ϕ and θ component of curl $\vec{F}$, also

$$\partial Z_n/\partial r = -(1/r)\left[2Z_n + \partial X_n/\partial\theta + X_n/\tan\theta + \partial Y/\sin\theta\,\partial\phi\right] \ldots\ldots\ldots (15)$$

obtained from div $\vec{F} = \nabla^2 V = 0$.

Second vertical derivatives are obtained by differentiating with respect to r in (13), (14) and (15). With changes of the order of differentiation, with respect to r and other variables, the respective second partials are

$$\partial^2 X_n/\partial r^2 = (1/r)\,[(\partial/\partial\theta)(\partial Z_n/\partial r) - 2\,\partial X_n/\partial r] \;\ldots\ldots\ldots\ldots\ldots \;(16)$$

$$\partial^2 Y/\partial r^2 = (1/r)[(\partial/\sin\theta\;\partial\phi)(\partial Z_n/\partial r) - 2\,\partial Y/\partial r] \;\ldots\ldots\ldots\ldots \;(17)$$

$$\begin{aligned}\partial^2 Z_n/\partial r^2 = \; & -(1/r)[3\,\partial Z_n/\partial r + (\partial/\partial\theta)(\partial X_n/\partial r) + \partial X_n/\tan\theta\,\partial r \\ & + \partial/\sin\theta\;\partial\phi)(\partial Y/\partial r)] \;\ldots\ldots\ldots\ldots\ldots\ldots \;(18)\end{aligned}$$

In these equations, the first vertical partial derivatives may be replaced by the appropriate expressions in (13), (14) or (15).

By additional differentiation all higher-order partial derivatives may be determined. Generally, difference quotients will be used in place of analytic derivatives since the fields are ordinarily not representable by functional relationships.

The extent and accuracy of the surface values of the components will limit the number of terms of the series in (10), (11), and (12) that should be used. The rapidity of convergence of the series depends on the complexity of the surface field and the height to which the extrapolation is made, but in general the remainder after a finite number of terms will be less than the value of the highest-order term used in the Taylor series. The extrapolated component-value secured by the partial Taylor series differs from the exact solution with spherical harmonics only in terms containing h^{q+1}, h^{q+2}, and so on, where q is the order of the highest-order derivative in the partial Taylor series.

For example, consider the upward continuation of the X_n component of a field with components defined by spherical harmonics in the following manner

$$X_n = -\Big[A_1\,(a/r)^3\;\partial P_1\,(\cos\theta)/\partial\theta + A_{600}\,(a/r)^{602}\;\partial P_{600}\,(\cos\theta)/\partial\theta\Big] \;\ldots.\;(19)$$

$$Z_n = 2A_1\,(a/r)^3\,P_1\,(\cos\theta) + 601\,(a/r)^{602}\,A_{600}\,P_{600}\,(\cos\theta) \;\ldots\ldots\ldots\ldots\ldots \;(20)$$

$$Y = 0 \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \;(21)$$

This field is that of the centered dipole field, whose components contain the term $P_1\,(\cos\theta)$, and of an anomaly field of about 30 km in north-south extent.

For a point at a height h above a point on the surface r=a, the X_n component is computable from (19), which may be written as an infinite power series in powers of h

$$\begin{aligned}X_n = \; & -A_1\,[\,\partial P_1(\cos\theta)/\partial\theta][1 - 3h/a + 3\cdot 4\,h^2/2!a^2 - 3\cdot 4\cdot 5\,h^3/3!a^3 + \ldots] \\ & - A_{600}[\,\partial P_{600}\,(\cos\theta)/\partial\theta][1 - 602\,h/a + 602\cdot 603\;h^2/2!\,a^2 - \;\ldots] \;\ldots\ldots\ldots \;(22)\end{aligned}$$

We have obtained the derivatives in the vertical direction by applying (13), (16), and expressions for higher-order partials to (19) and (20). Because of the uniqueness of the power series, the Taylor series of (10) is identical term by term with the series in (22); and the following equalities hold

$$\left.\begin{aligned}X_{n(r=a)} &= -A_1\;\partial P_1\,(\cos\theta)/\partial\theta - A_{600}\;\partial P_{600}\,(\cos\theta)/\partial\theta \\ (\partial X_n/\partial r)_{r=a} &= 3A_1\;\partial P_1\,(\cos\theta)/a\,\partial\theta + 602A_{600}\;\partial P_{600}\,(\cos\theta)/a\,\partial\theta \\ (\partial^2 X_n/2!\,\partial r^2)_{r=a} &= -\,3\cdot 4\;A_1\;\partial P_1\,(\cos\theta)/2!\,a^2\partial\theta \\ &\quad - 602\cdot 603\;A_{600}\;\partial P_{600}\,(\cos\theta)/2!\,a^2\,\partial\theta\end{aligned}\right\}\;\ldots\ldots\ldots\;(23)$$

and so on. The derivatives with respect to r in (23) are, of course, identical with those secured by differentiating with respect to r the expression for X_n in (19).

Therefore, a partial Taylor series of, for example, three terms would differ from the infinite series of (22), the exact solution, by terms containing h in powers larger than two. These considerations, although applied here to a component described by two spherical harmonics, are equally applicable to a field whose description requires a large number of harmonics.

A sample calculation with the Taylor series and with spherical harmonics may be readily made in the simple case of an upward continuation of the X_n component of the dipole field in (19) and (20). By spherical harmonics, with Vestine's coefficients, this component may be calculated for any point at a height h above the surface of the Earth from

$$X_n(h) = -31{,}200 \sin\theta\,(a/a+h)^3 \times \gamma$$

$$= -31{,}200 \sin\theta\,[1 - 3h/a + 3\cdot 4\, h^2/2!\,a^2 - 3\cdot 4\cdot 5\, h^3/3!\,a^3 + \ldots] \quad \ldots (24)$$

where a is the radius of the Earth, about 6370 km, and one gamma = 10^{-5} cgs unit.

With the partial derivatives with respect to r determined by applying (13) and (16) to the dipole components in (19) and (20), a Taylor series of three terms gives

$$X_n(h) = -31{,}200 \sin\theta\,[1 - 3h/a + 3\cdot 4\, h^2/2!\,a^2] \quad \ldots\ldots\ldots\ldots (25)$$

The value of the X_n component at height h and latitude θ of, say, 100 km and 45° respectively, is - 21,055 γ by (25). This value differs by approximately one gamma from that obtained with (24).

For a vertical continuation toward the sources of magnetism that are inside the Earth, the same fundamental equations, with the substitution of -h for +h in the Taylor series, are applicable in regions external to the actual sources. After the components of the intensity are calculated for points either above or below a measured surface, additional magnetic elements are computable from the values of the components.

Sometimes when treating the Earth's magnetic field, particularly anomalies over small areas, it is convenient to assume that this surface is a plane and that the field components have a fixed direction. These assumptions are not valid in the present method of extrapolation. For example, assume that a rectangular coordinate system is so chosen that the elements of arc dx, dy, and dz are, respectively, equal to the elements rdθ, r sin θ dϕ, and dr. From the equations for the divergence and curl of F in rectangular coordinates, the first vertical derivatives are

$$\left.\begin{aligned} \partial Y/\partial z &= \partial Z_n/\partial y \\ \partial X_n/\partial z &= \partial Z_n/\partial x \\ \text{and} \qquad \partial Z_n/\partial z &= -[\partial X_n/\partial x + \partial Y/\partial y] \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (26)$$

These values differ from those of (13), (14), and (15), and hence would be in error by the nonderivative terms such as $2Z_n/r$ in (15), which generally are not negligible.

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A NEW SOLUTION OF THE INVERSE SHORAN PROBLEM

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Abstract--There are two general types of shoran computations: (1) the direct case, in which the shoran dial reading, the aircraft altitude, and other pertinent data are photographed on recorder film, and the data subsequently reduced to the geodetic distance, and (2) the inverse case, in which the geographic coordinates and altitude of ground station and aircraft are furnished, while the corrected shoran dial setting is desired. It is a solution to this second problem which is presented herein with a new approach which the author has chosen to name the 'parallel radius method.' The surface of the Earth is by-passed completely and computations are simple and rapid without loss of accuracy.

In certain phases of shoran activity, the following problem is encountered

Given:
ϕ_1, λ_1 = geodetic coordinates of the shoran ground station antenna, hereafter referred to as Station 1
ϕ_2, λ_2 = geodetic coordinates of the shoran airborne station, hereafter called Station 2
K = altitude of the shoran antenna at Station 1
H = altitude of the shoran antenna at Station 2 on a specified reference ellipsoid

Find: The corrected shoran dial setting S_d at Station 2.

In the past, a variety of computational methods have been used. USC and GS Forms 662 and 662a (logarithmic and machine, respectively) have proved very reliable for the inverse geodetic problem, followed by the geometric correction to the shoran ray path and the velocity correction to account for the variation in propagation velocity from the design standard. This method is somewhat laborious and time consuming. Computer personnel with limited mathematical background find it difficult to understand and generally accomplish the solution by rote.

Methods based on Universal Transverse Mercator coordinates have been used with a measure of success. While offering some advantage in speed, there are certain inherent problems such as zone to zone transformations and scale factors.

More recently, methods based on geocentric space rectangular coordinates have attained some popularity. These methods solve directly the chord of the shoran ray path without reference to the geodetic distance. To this chord distance, the combined geometric and velocity correction is applied to obtain the shoran dial setting. Proponents of these space coordinate methods have had difficulty in the past in perfecting a simple azimuth solution.

The inverse shoran solution should combine as much as possible the four virtues of accuracy, speed, simplicity, and dependability. Accuracy must be held within standards dictated by the mission being performed and the ability of the equipment to receive the data. Speed is important when computing under mass-production conditions. The method should be understandable to computer personnel and as free from tedium as possible. Under dependability may be listed such factors as adaptability to logarithmic form in case of calculating machine failure or destruction, and availability of tables and computing aids.

The parallel-radius method offers a unique combination of these four virtues. Like the methods based on space rectangular coordinates, it by-passes the Earth's surface. Its explanation requires four logical steps, three to explain how the shoran dial setting is obtained and one step to show the azimuth determination.

Step 1: From geodetic coordinates to the chord of the ellipsoid--Consider two points P_1 (ϕ_1, λ_1) and P_2 (ϕ_2, λ_2) on the surface of the ellipsoid as shown by Figure 1. The intersection of the parallel of latitude through P_1 with the meridian through P_2 is designated P_1'. The intersection of the parallel of latitude through P_2 with the meridian through P_1 is designated P_2'. The center of the parallel of latitude through P_1 is O_1. The center of the parallel of latitude through P_2 is O_2. Both O_1 and O_2 lie on the polar axis.

The segment $O_1 - O_2 - P_2 - P_2' - P_1 - P_1'$ of the ellipsoid is removed and enlarged to produce Figure 2. The four points P_1, P_1', P_2 and P_2' are joined, thus producing four chords which form a trapezoid within the ellipsoid. The radii of the parallels of latitude through P_1 and P_2 are designated R_{P_1} and R_{P_2}, respectively.

The length of chords c_1 and c_2 are

$$c_1 = 2 \times \sin(\Delta\lambda/2) \times R_{P_1} \quad \ldots\ldots\ldots\ldots (1)$$

$$c_2 = 2 \times \sin(\Delta\lambda/2) \times R_{P_2} \quad \ldots\ldots\ldots\ldots (2)$$

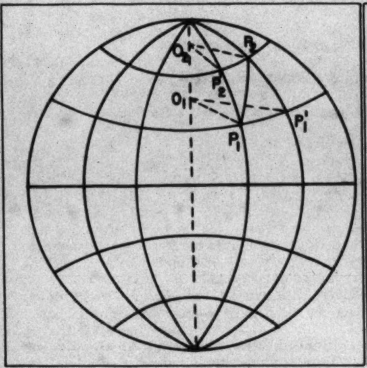

Fig. 1--Elements of parallel radius method

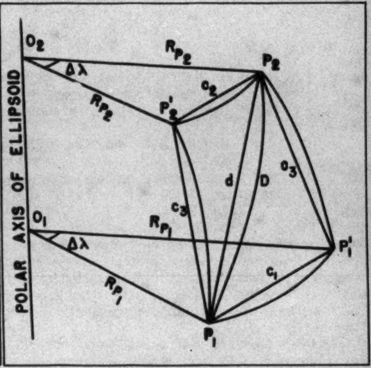

Fig. 2--Portion of ellipsoid removed and enlarged

The two remaining sides of the trapezoid are equal in length to each other and are designated c_3. Figure 3 shows a meridional plane. The chord c_3 is obtained by

$$c_3 = \sqrt{(R_{P_1} - R_{P_2})^2 + (y_2 - y_1)^2} \quad \ldots\ldots\ldots\ldots (3)$$

Geodesists will recognize that the parallel radius is the standard x value of the ellipsoid and is given by

$$R_P = x = a \cos\phi / \sqrt{1 - e^2 \sin^2\phi} \quad \ldots\ldots\ldots\ldots (4)$$

while the y value is expressed by

$$y = a(1 - e^2) \sin\phi / \sqrt{1 - e^2 \sin^2\phi} \quad \ldots\ldots\ldots\ldots (5)$$

For the parallel-radius method to be rapid, values of x and y must be readily available in tabular form. To this end, tables were prepared giving x and y to the fourth decimal part of a mile for each minute of latitude from equator to pole. Since the shoran dial setting is in statute miles, it was natural to prepare the tables in that unit. First the x values were computed, then y values were obtained by

$$y = x(1 - e^2) \tan\phi \quad \ldots\ldots\ldots\ldots (6)$$

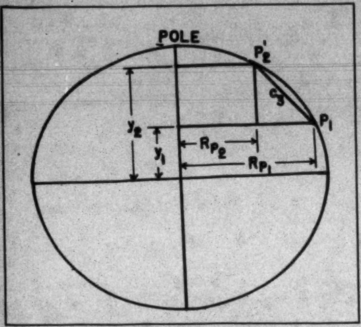

Fig. 3--Meridional plane

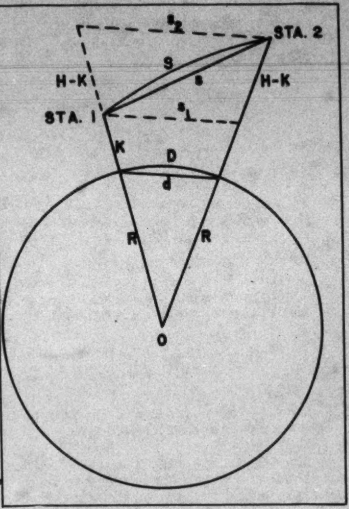

Fig. 4--Ray path in profile

which is the expression relating x and y. Computation of these values was accomplished by personnel of the Mapping and Charting Research Laboratory of Ohio State University using IBM equipment.

With all four sides of the trapezoid now known, the chord which connects P_1 and P_2 is obtained by

$$d = \sqrt{c_1c_2 + c_3^2} = \sqrt{c_1c_2 + (\Delta x)^2 + (\Delta y)^2} \quad \ldots (7)$$

Step 2: From the chord of the ellipsoid to the chord of the shoran ray path--In order to simplify the subsequent development the points P_1 and P_2 are now assumed to lie on a sphere of suitable dimensions. Consider Figure 4 which is formed by passing a plane through Station 1 which is K distance above sea level, through Station 2 which is H distance above sea level, and through the center O of an assumed spherical Earth. The true length d was obtained in Step 1. D is the geodetic distance, by-passed completely in this solution. S is the length of the shoran ray path, uncorrected for velocity variation, while s is the chord joining Station 1 and Station 2.

Through Stations 1 and 2, lines are constructed parallel to d. The remainder of the dotted construction is completed. It is obvious that a trapezoid has been formed with sides of length s_1, s_2, H - K and H - K. Since H and K are given quantities, two sides are available at once. The other two sides are obtained by

$$\left.\begin{aligned} s_1 &= [(K + R)/R] \times d \\ s_2 &= [(H + R)/R] \times d \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

The required chord distance is

$$s = \sqrt{s_1s_2 + (H - K)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Step 3: From the chord of the shoran ray path to the shoran dial setting--In order to arrive at the shoran dial setting, there must be applied to the chord distance s a geometric correction to obtain the arc S, followed by a velocity correction to account for the increase in velocity with altitude. These two corrections are generally lumped together into a combined geometric-velocity correction. This matter will not be discussed further because nothing new is offered here and because adequate equations, graphs, and tables are already in existence. It is recommended that graphs or tables, such as those prepared by Omar O. Fickeissen of the 1370th Photo Mapping Group of the U. S. Air Force, be used to obtain the combined correction.

Step 4: Determination of azimuth--In the inverse shoran problem, only the azimuth from Station 2 to 1 is required. To obtain α_{2-1}, the azimuth equation of Rudoe as presented by BOMFORD [1952] was used:

$$\cot \alpha_{2-1} = \left[\frac{\tan \phi_1}{(1+\epsilon)\tan \phi_2} + e^2 \frac{N_2 \cos \phi_2}{N_1 \cos \phi_1} - \cos \Delta\lambda \right] \frac{\sin \phi_2}{\sin \Delta\lambda} \quad \ldots\ldots (10)$$

where

$\epsilon = e^2/(1 - e^2)$
e^2 = square of eccentricity = $(a^2 - b^2)/a^2$
N_1 = radius in the prime vertical at ϕ_1
N_2 = radius in the prime vertical at ϕ_2

However, $N_1 \cos \phi_1$ is equal to x_1 and $N_2 \cos \phi_2$ is equal to x_2, both of which have been obtained in the distance computation. Substituting the values of the constants ϵ and e^2 for the Hayford International Ellipsoid, the azimuth equation becomes

$$\cot \alpha_{2-1} = \left(\frac{\tan \phi_1}{1.00676817 \tan \phi_2} + 0.00672267 \frac{x_2}{x_1} - \cos \Delta\lambda \right) \frac{\sin \phi_2}{\sin \Delta\lambda} \quad \ldots (11)$$

In this solution, the sign of $\sin \Delta\lambda$ must be taken in the sense $\Delta\lambda = \lambda_2 - \lambda_1$ when working with west longitude. For east longitude, $\Delta\lambda = \lambda_1 - \lambda_2$.

Since the least setting of azimuth in the airborne set is $0^\circ.01$, or 36", there is no reason to carry the azimuth solution to a higher degree of precision than the equipment can utilize. It has been determined that five-place natural functions will be sufficiently accurate to stay within the $0^\circ.01$ tolerance.

Summary--This method has been tested in actual operations with seven-place natural functions (five-place in the case of the azimuth) and a portable, hand-operated, eight-row calculating machine. For most cases involving the inverse shoran problem, this equipment will give sufficient accuracy. However, eight-place natural functions and a ten-row calculating machine are recommended. There are two square-root solutions in the process of performing the distance computation. Therefore, a calculating machine with accumulative multiplication and automatic square root extraction features is recommended.

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NET DESIGN FOR HIRAN SURVEYS

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Abstract--Problems involved in the design of nets for hiran (high accuracy shoran) surveys are set forth. Factors are suggested which may be used in the development of criteria for classification of trilateration as to order of accuracy. A method for computing the strength of figure of a trilateration net and an interim accuracy criterion for planning nets for first-order surveys are proposed. The methods and procedures currently used by personnel of the 1370th Photo-Mapping Group in net design are discussed.

Introduction--Aerial electronic surveying is a function of the 1370th Photo-Mapping Group, Air Photographic and Charting Service, Military Air Transport Service, United States Air Force, which utilizes hiran equipment to measure distances included in trilateration networks. The successful completion of extensive arcs of trilateration has led to a demand for the widespread use of hiran to establish geodetic control over broad areas where no control now exists and to perform datum ties hitherto believed impossible.

The magnitude of current and proposed hiran projects and the difficulties inherent in them make the proper design of trilateration nets of increasing importance. The primary problems involved are: (1) a definition of first-order accuracy for hiran surveys; and (2) design of hiran nets to meet the accuracy requirements in the most economical manner.

An accuracy yardstick--Trilateration projects accomplished in the past, and scheduled for the future, have included the requirement of first-order accuracy. The term 'first-order accuracy' as applied to hiran trilateration has never been clearly defined but it may be assumed that the requirement specifies the determination of geographic positions with the same accuracy as their determination by a first-order triangulation survey of similar extent.

The criteria for first-order triangulation include specified base closures, triangle closures, strength of figure considerations, etc., and triangulation accuracy over long distances is maintained by strict adherence to these established criteria. The specifications do not ordinarily involve proportional-part accuracy for arcs of triangulation hundreds or thousands of miles in length. Estimates of the accuracy of long arcs of triangulation may be based on results of adjustments of extensive triangulation networks and the closures determined thereby. SIMMONS [1951] has proposed an empirical formula which may be used to give an indication of the proportional-part accuracy to be expected of distances computed between two points joined by a first-order triangulation net. The formula is

$$\text{Proportional-part accuracy} = 1{:}20{,}000\ \sqrt[3]{M} \quad \ldots\ldots\ldots\ldots\ldots (1)$$

where M is the distance in miles.

A somewhat similar formula has been used by Army Map Service. This formula modified to show proportional-part accuracy is

$$\text{Proportional part accuracy} = 1{:}0.846\ \sqrt{M} \times 10^4 \quad \ldots\ldots\ldots\ldots (2)$$

Proportional-part accuracy computed from these formulas is not to be considered as either the minimum or maximum accuracy of a triangulation net but merely the usual results. The two formulas are not completely in agreement; however, they are sufficiently similar and give some indication of the accuracy of long arcs of triangulation and therefore of the accuracy which should be expected from hiran projects.

The absolute accuracy of a net of trilateration is difficult to determine. Some estimation may be given by a comparison of distances and azimuths determined from a hiran net with distances and azimuths fixed by triangulation. Such comparisons are not always available. The final results of a trilateration survey are geographic positions. The accuracy of these positions should provide the most comprehensive measure of the overall accuracy of the electronic survey. The relationship between probable-position errors and distance along the axis of the net should supply an accuracy yardstick. A comparison of this relationship with the expected proportional-part accuracy of a net of triangulation of similar extent should provide a sound basis for an estimate of net strength necessary to meet first-order trilateration requirements.

Criteria for trilateration--The problem of classifying hiran trilateration as to order of accuracy may be divided into two parts: (1) the establishment of a criterion which would serve as a measure of the accuracy of hiran observations; and (2) the establishment of a measure of the strength of the configuration of a trilateration network. The absolute accuracy of hiran measurements of lines whose lengths are not known is difficult to determine. The problem of net configuration is one of simple geometric construction.

Unknowns solved for in a trilateration adjustment are shifts in latitude and longitude for the various points in the net. The probable errors of these position shifts may be computed from the formula:

$$PE = PE_s \cdot \sqrt{1/W}$$

where PE_s = the probable error of a single observation, W = the computed weight of an equation corresponding to a shift in latitude or longitude.

The factor $\sqrt{1/W}$ is altogether a function of the configuration of the net and is not affected by the accuracy of the hiran measurements. It may be likened to the factor

$$\frac{D - C}{D} \times \Sigma \left[\delta_A{}^2 + \delta_A \ \delta_B + \delta_B{}^2\right]$$

in the equation

$$p^2 = \frac{4}{3} d^2 \times \frac{D - C}{D} \times \Sigma \left[\delta_A{}^2 + \delta_A \ \delta_B + \delta_B{}^2\right] \quad \ldots\ldots\ldots(3)$$

which is the R or strength factor used in determining the strength of triangulation nets. Computation of the factor 1/W for each position shift will serve to indicate the relative strength of every point in the net and the overall strength of the net as a whole due to the geometry of its construction. These factors may be computed in an adjustment process. An example of the computation is given in Hiran Surveying Handbook [FIRST COMPUTATIONS TECHNICAL SQUADRON, 1954].

The other factor in the formula for the probable error of a position shift is the probable error of a single observation. The PE_s is primarily a function of the accuracy of hiran measurements but is also affected somewhat by net configuration. For measurements of equal accuracy the magnitude of PE_s will tend to be smaller for weak nets as less of the errors of observation will be recovered in the form of corrections. Any comparison of the PE_s for two nets should take into consideration the relative strength of figure of the nets. Once the strength of figure has been established by computation of the factors $\sqrt{1/W}$, valid comparisons of PE_s may be made and a criterion for a maximum value of PE_s established. Net adjustments of past hiran projects have given values of PE_s ranging from ±0.0019 mile to ±0.0029 mile. It should reasonably be expected that values for PE_s resulting from current and future projects will be very little in excess of ±0.0025 mile.

Until a specific criterion for first-order trilateration has been adopted and generally accepted an interim criterion is required for planning. The one presently in use may be expressed

$$\frac{\sqrt{(PE_\phi)^2 + (PE_\lambda)^2}}{\text{Distance from fixed position (miles)}} \cong \frac{1}{20{,}000 \sqrt[3]{M}} \quad \ldots\ldots(4)$$

Net design--The project requirements are the basis for any net design. Electronic surveys are usually accomplished for a specific purpose and the accuracy necessary to accomplish the purpose is usually specified. The accuracy specified for past and current projects has been first-order. The interim criteria for first-order trilateration may be used to interpret this requirement for the purpose of net construction. As little guess work as possible should be used in net design and it should be certain that the accomplished survey will fully meet the project requirements.

The need for a scientific approach to the problem of net design was pointed out by a comparison of the published results of the Scotland - Norway Tie [FIFTY-FIFTH STRATEGIC RECONNAISSANCE WING, 1953] and the Crete - North Africa Tie [HEADQUARTERS AIR PHOTOGRAPHIC AND CHARTING SERVICE, 1954]. The two nets were almost identical in extent and configuration; however, the Scotland - Norway Tie was the stronger due to the availability of an additional length and azimuth condition. This additional strength is shown in the results (Table 1).

Table 1--Comparison of results of two ties

Item	Scotland - Norway	Crete - North Africa
PE_ϕ	± 0.00160 mile	± 0.00129 mile
PE_λ	± 0.00068 mile	± 0.00306 mile
$\sqrt{(PE_\phi)^2 + (PE_\lambda)^2}$	± 0.00174 mile	± 0.00332 mile
Axial distance	280 miles	255 miles
Proportional part	1:161,000	1:77,000

In each case the interim criterion would have given a proportional part accuracy of about 1:130,000. This is not meant to imply that the results of the Crete - North Africa Tie were not adequate for the purpose but to indicate that better results could have been attained by a slight strengthening of the project net. Note that for tie the uncertainty in the direction perpendicular to the net was more than double the uncertainty in the direction of the axis of the net.

Since the method for computing the strength of a figure does not require hiran observed distances, the computation may be made before the start of a project utilizing estimated azimuths as starting data. By computing the factors $\sqrt{1/W}$ and assuming a value for PE_s based on past experience the adequacy of a proposed net to meet the project requirements may be ascertained. The relative strength of every point may be determined and indicated weaknesses should point the way for net modification. The direction of strength and of weakness for each point would be evident from the magnitude of the factor $\sqrt{1/W}$ for the shifts in latitude and longitude. Lines which should be included or could be eliminated may be identified. The solution for the weights may also include equations for constant and systematic errors. Since the approximate probable errors for constant and systematic errors may be computed, the capability of a net design to allow an accurate determination of the existence and magnitude of such errors may be concluded.

A net should be designed to make the best use possible of hiran measurements and to minimize the effect of possible inaccuracies by allowing the identification of such inaccuracies. The type of project ordinarily accomplished by hiran will usually preclude the adoption of the theoretically best net configuration. Figure modifications are usually due to the following factors: (1) the necessity for the inclusion of all basic requirements, including specified locations for ground stations; (2) the adoption of sites for ground station installation must take into consideration accessibility, logistics, terrain features, and siting desirability from the electronic standpoint; and (3) availability of station sites; for example, islands are not always so located as to form the best figure.

Although the availability of possible station locations will modify to a great extent any theoretically best net design, such a design should be useful in planning the construction of networks. Some tests have been made of a basic six-pointed figure which has a somewhat greater dimension perpendicular to the axis of the net than the dimension in the direction of the axis. Each figure would extend the net about 250 miles, four interlocking figures providing a 1,000-mile net. Tests indicate that quite a few long lines interlocking the various figures are required to maintain strength adequately. By interlocking the figures various thin triangles are usually formed which are of aid in the determination of the existence and magnitude of any constant error.

A complex figure such as has been described is necessary to supply sufficient conditions to insure the accurate determination of positions. For a strong net, the ratio of observations to unknowns should be about three to one; or, if no fixed conditions are present, there should be about four redundant lines for each position to be determined. The basic figure for triangulation is the quadrilateral which contains four conditions, or two for each position to be determined. The ratio is lower than that recommended for trilateration but is increased somewhat by the inclusion of length, azimuth, latitude, and longitude conditions at intervals. The figure recommended for trilateration is stronger than that for triangulation. Figure strength required is, however, directly dependent on the accuracy of the observations. Checks such as triangle closures allow the precision of the triangulation measurements to be maintained at a very high level. Lack of such checks on hiran observations makes mandatory a strong net figure, as the only measure of precision is through the adjustment process.

The strength of an individual point is greatly dependent on the number of lines terminating at that point and the azimuth of those lines. An interior point with lines coming into it from all directions is likely to be more accurately positioned than a point on the periphery of the net. To eliminate weak links it is ordinarily preferable to spread the strength evenly throughout the net by making equal the relative strength of all points. The number of lines used to position a point will be dependent on the accuracy required. A really strong net requires a ratio of observations to unknowns of about three to one. There are two unknowns for each new point. This means that, if the observations are evenly divided, each new point should be the terminus for about twelve lines if all of the lines are to other points also to be positioned. This number is approximate and will vary in specific instances. Some factors to be considered are: (1) lines to fixed positions have greater weight; (2) two points tied by a fixed length or a fixed azimuth total only three unknowns; and (3) two points tied by both a fixed length and a fixed azimuth total two unknowns. To equalize the strength of the various points further it may be necessary to drop a few lines terminating at centrally located points and assign those lines to points on the periphery of the net.

Fixed conditions--It should be possible, at least theoretically, to design a trilateration net of sufficient complexity so that the inclusion of fixed conditions would be unnecessary. It is, however, certainly economical to utilize fixed conditions to provide strength and thus reduce the number of hiran measurements required. Hiran nets should be planned and ground stations located to make the best possible use of any existing control. A triangulation net which covers merely an isolated island or group of islands may yet furnish a fixed length and azimuth which will help orient the trilateration net as a whole.

A fixed azimuth serves to orient the net and a fixed distance serves as a scale for the hiran measurements. The longer the line for which there is a fixed azimuth the better will be the orientation. An azimuth may be obtained astronomically for a line whose terminals are intervisible; however, the insertion of an additional station into the net to obtain an azimuth over a very short line would appear to be a mistake. The effect on the orientation of the net of an azimuth over a very short line is relatively small. The additional lines required to fix the extra point would be of more value if they were measured between the original points and the extra point was omitted. If the azimuth could be observed between required points or between points of sufficient elevation to allow azimuth observations over relatively long lines, the fixed condition so obtained would be of great value. For a longer line the interpolation of a Laplace azimuth and a net of triangulation is very satisfactory. An example of this type of procedure is the triangulation survey on Grand Bahama Island used to supply fixed data for the Florida - Puerto Rico net.

In past projects, large triangulation networks have been included as integral portions of the hiran nets. Their inclusion was dictated to some extent by the necessity for the completion of a well-rounded net; however, the primary effect was to reduce the number of hiran measurements required for a net of adequate strength. Nets without triangulation have been relatively weak and there have been few opportunities to obtain valid measures of the ability of strong nets composed entirely of trilateration to carry forward an azimuth. The completion of a project proposed for the near future should allow a very good comparison of azimuths determined astronomically and those determined by an adequate trilateration net.

The necessity of relying on the completion of triangulation surveys to supply fixed conditions has resulted in difficulties in coordination. Control is extended so rapidly by hiran that a project is usually completed before the fixed data is available. Final evaluation of the consistency of the hiran measurements has often been delayed awaiting completion of a triangulation survey or adjustment. A method of supplying azimuth control which is within the capabilities of the hiran organization should facilitate the extension of primary control. The technique of azimuth determination through the use of flares could be such a method, if proven successful in tests.

Proper insertion of condition equations into a computation of figure strength will permit an evaluation of the effect of fixed conditions on the determination of positions. Before extensive ground surveys are performed for the specific purpose of providing fixed lengths and azimuths for a trilateration net, the necessity for such fixed conditions should be established beyond doubt.

Table 2--Results of strength-of-figure computation (assumed value of PE_s = 0.0025 mile)

Station	Direction	1/W	$\sqrt{1/W}$	PE ±	$\sqrt{PE_\phi^2 + PE_\lambda^2}$ ±	Distance from fixed positions	Proportional part	Simmons' formula
				mi	mi	mi		
6	Latitude	0.23	0.48	0.00120	0.00184	201	1:109,000	1:117,000
	Longitude	0.32	0.56	0.00140				
7	Latitude	0.19	0.43	0.00109	0.00188	201	1:107,000	1:117,000
	Longitude	0.38	0.61	0.00153				
8	Latitude	0.20	0.45	0.00112	0.00218	296	1:136,000	1:133,000
	Longitude	0.56	0.75	0.00187				
9	Latitude	0.60	0.78	0.00194	0.00257	402	1:156,000	1:148,000
	Longitude	0.45	0.67	0.00168				
10	Latitude	0.57	0.75	0.00188	0.00277	414	1:149,000	1:149,000
	Longitude	0.66	0.81	0.00203				
11	Latitude	0.44	0.67	0.00167	0.00302	497	1:165,000	1:158,000
	Longitude	1.02	1.01	0.00252				
12	Latitude	0.94	0.97	0.00242	0.00326	568	1:174,000	1:166,000
	Longitude	0.77	0.88	0.00219				
13	Latitude	0.94	0.97	0.00242	0.00326	508	1:156,000	1:160,000
	Longitude	0.77	0.88	0.00219				
14	Latitude	1.42	1.19	0.00298	0.00360	605	1:168,000	1:169,000
	Longitude	0.65	0.81	0.00202				
15	Latitude	1.17	1.08	0.00270	0.00425	780	1:184,000	1:184,000
	Longitude	1.72	1.31	0.00328				
16	Latitude	1.84	1.36	0.00339	0.00419	757	1:181,000	1:182,000
	Longitude	0.97	0.98	0.00246				
17	Latitude	2.42	1.56	0.00389	0.00449	828	1:184,000	1:188,000
	Longitude	0.81	0.90	0.00225				
18	Latitude	2.42	1.55	0.00389	0.00481	875	1:182,000	1:191,000
	Longitude	1.28	1.13	0.00283				
19	Latitude	1.92	1.38	0.00346	0.00501	922	1:184,000	1:195,000
	Longitude	2.10	1.45	0.00362				
20	Latitude	3.01	1.74	0.00434	0.00533	993	1:186,000	1:200,000
	Longitude	1.54	1.24	0.00310				
21	Latitude	2.82	1.68	0.00420	0.00568	1055	1:186,000	1:204,000
	Longitude	2.33	1.53	0.00382				
22	Latitude	2.82	1.68	0.00420	0.00568	1088	1:192,000	1:206,000
	Longitude	2.33	1.53	0.00382				
23	Latitude	3.16	1.78	0.00445	0.00605	1159	1:192,000	1:210,000
	Longitude	2.68	1.64	0.00410				
24	Latitude	3.94	1.98	0.00496	0.00635	1265	1:199,000	1:216,000
	Longitude	2.52	1.59	0.00397				
25	Latitude	4.37	2.09	0.00523	0.00654	1348	1:206,000	1:221,000
	Longitude	2.47	1.57	0.00393				
26	Latitude	4.17	2.04	0.00510	0.00659	1348	1:205,000	1:221,000
	Longitude	2.78	1.67	0.00417				
27	Latitude	3.47	1.86	0.00466	0.00643	1324	1:206,000	1:220,000
	Longitude	3.14	1.77	0.00443				
28	Latitude	3.62	1.90	0.00475	0.00673	1419	1:211,000	1:225,000
	Longitude	3.64	1.91	0.00477				
29	Latitude	5.32	2.31	0.00577	0.00723	1549	1:214,000	1:231,000
	Longitude	3.04	1.74	0.00436				
30	Latitude	5.32	2.31	0.00577	0.00723	1608	1:222,000	1:234,000
	Longitude	3.04	1.74	0.00436				
31	Latitude	4.73	2.17	0.00544	0.00720	1561	1:217,000	1:232,000
	Longitude	3.55	1.88	0.00471				
32	Latitude	4.85	2.20	0.00550	0.00741	1691	1:228,000	1:238,000
	Longitude	3.94	1.98	0.00496				
33	Latitude	5.32	2.31	0.00577	0.00723	1738	1:240,000	1:240,000
	Longitude	3.04	1.74	0.00436				
34	Latitude	5.32	2.31	0.00577	0.00723	1774	1:245,000	1:242,000
	Longitude	3.04	1.74	0.00436				

Procedure summary--The procedure followed in the design of a net for a current survey has also been used for the North Atlantic Tie and is advocated for future projects. The survey is based on a requirement for the establishment of a first-order trilateration net to extend for approximately 2400 miles and to serve as primary control for a vast area. The procedure followed in the design of the net is summarized.

(1) Determination of the project requirements.

(2) Research to locate possible station sites.

(3) Tentative design of net based on adopted basic figure and with a ratio of observations to unknowns of approximately three to one.

(4) Test of adequacy of net by computation of factor $\sqrt{1/W}$ for each unknown.

(5) Modification of the net on the basis of the computation of figure strength.

(6) Further net modification as required by the results of the field reconnaissance. An example of the results of the strength of figure computation for a portion of a survey is shown in Table 2. The comparison of computed proportional-part accuracy with the adopted standard is believed to indicate that the net is about of the right complexity and proper configuration to fully meet the requirements for first-order accuracy.

Conclusions--The basic problems of net design are the determination of exactly what is required for first-order trilateration and the adequacy of a net to meet that requirement. It is believed that the suggested interim criteria will suffice for the present to indicate the accuracy required and that the strength of figure computation will supply a measure of the ability of a net to meet the criteria. A definitive accuracy criterion for trilateration should, perhaps, await a greater accumulation of experience in hiran surveying. The factors mentioned could, however, be used in the development of such a criterion.

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DISCUSSION

J. E. R. Ross (Geodetic Survey of Canada, Ottawa, Canada)--I agree in principle with everything that has been said and, like the writer, think that we shall have to await more extensive nets of trilateration before we can assess the actual accuracy. It is one thing to approach accuracy by empirical formulas and to be satisfied with the indicated result but quite another thing to be confounded with an example where for some unknown reason the results are very much inferior. This has happened in cross-bars of triangulation loops and undoubtedly will exist in trilateration.

In our northern Shoran net we have deliberately run away from chains of trilateration and performed the work on a widespread area basis. I think that the final placement in position will show the wisdom of this.

I heartily agree that the number of lines radiating from a point should be high and the attachment of each season's work to exterior points with very few lines used in their preliminary determination indicates in a general way that no position is accurate if it has not at least five lines used in its determination. It is less accurate if these lines form a sector such as 90 or 120° than when the lines cover the entire 360°-field. Another way of expressing this would be to say that an interior point would be more accurate than an exterior point for the same number of lines.

We agree that short azimuth lines are not as effective in maintaining azimuth as long lines but our experience indicates that even short lines of 20 miles do exercise a considerable degree of control and that we would have been worse off if we had not used them on three occasions. Our most northerly azimuth control, apart from those obtained through triangulation, is about 47 miles in length and is used as a principal line in the net rather than as an auxiliary. The ratio of expansion in line length in this case in the immediate vicinity is of the order of 1 to 4 and undoubtedly places the framework in that locality in proper orientation and it is hoped has improved the accuracy of fixation.

We have just completed the trilateration of the Yukon area and will prepare the data for a unit adjustment of our six seasons' operations. This unit net will be based on some 18 geodetic attachments and be forced within the positions indicated by the triangulation. At the present time I would hesitate to specify what our outside error in position will be, as the measurements have been made by the modified Shoran equipment in which it is recognized that Hiran is an advance and capable of better accuracy.

The complexity of measurement indicates that an inferior line may produce quite a variation in position with detriment in azimuth which is increased in the subsequent projection of the chain. I think that the estimate of this type of error has been agreed upon and confirmed by Aslakson and ourselves in our respective works. In other words azimuth control is needed, and any chain by Hiran or Shoran must have azimuth control either at its terminal or within it, and preferably both.

Owen has given us an interesting paper which will bear study. In so doing, he would be the first to deny that the whole story is fully known. It is likely that many definite opinions are going to be sharply revised as more and more triangulation nets are placed within trilateration nets. We are not averse to modification of opinions, as this is the way of progress, and an open mind should and must be kept.

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MEAN AIRFLOW AND HEAT TRANSPORT PATTERNS GENERATED BY WIND MACHINES WITH APPLICATIONS TO FROST PROTECTION

George Allen Baker, Jr.

Abstract--In this paper we develop theoretical flow patterns for idealization of several types of wind-machine settings of particular interest in the field of the wind-machine protection of fruit orchards from frost damage. We further develop from dimensional analysis and asymptotic considerations a semi-empirical formula for the effective velocity of a turning jet. We compute the time of arrival of air from a turning jet and by considering its relation to the transport we establish a semi-empirical formula relating the thermal response (a measure of the heat transported) to the mean arrival time.

Introduction--In recent years wind machines have been used extensively to provide frost protection for fruit orchards. The ability to provide protection depends on the existence of warmer air above the orchard. The wind machine essentially blows this warmer air down into the trees. A common design of wind machine (Fig. 1) consists of a motor-driven propeller mounted on the top of a tower some 30 to 35 ft tall. The direction of the thrust is some five to ten degrees below horizontal so that the blast of air strikes the trees at some distance from the tower. The whole top of the wind machine rotates slowly about a vertical axis with a period of about four or five minutes so that a larger area may be protected than is possible with a stationary wind machine. A certain amount of experimental work has been done to discover the quantitative relationships between the various factors involved. To date there has been almost no theoretical work. In this paper we shall develop certain formulas pertaining to the single, turning wind machine. Also some aspects of the stationary wind machine and of multiple settings of turning wind machines will be considered.

Stationary jet--In order to try to obtain a physical intuition for the magnitudes and factors involved, let us consider the relatively simple problem of a stationary jet operating in a quiet body of air with a linear temperature gradient in the vertical direction. This jet will be imagined to have a line of thrust which makes a small angle with the horizontal. (As is well known, the flow pattern of a wind machine closely resembles that of a jet.)

The problem of a stationary jet in an isothermal environment has been extensively studied. We will cite a few of its more important properties. An idealized jet is, of course, nothing more than a momentum source. Hence, the solution of the air-flow problem for all possible jets may be obtained by multiplying the solution for the velocity field of one by a dimensionless parameter, which is simply the ratio of the respective strengths of the momentum sources. Both theory and experiment show that, as long as the Reynolds number is sufficiently high, the boundary of a jet takes the form of a cone, with an included angle of about 24° [TOLLMIEN, 1926]. (For lower Reynolds number the cone will tend to have a larger included angle.) We shall simply assume that, when subjected to a linear temperature gradient, it retains essentially this conical shape. By Archimedes' principle a cylindrical slice (perpendicular to the axis of the cone) has a force per unit volume exerted on it equal to $g(\rho - \rho_1)$, where g is the acceleration due to gravity, ρ the density of the slice, and ρ_1 the density of the displaced fluid (air). We know [LAMB, 1945] that the effective mass per unit volume is the actual mass plus the virtual mass, approximately $\rho + \rho_1$. Hence, if y denotes the height of the centroid, we have

$$\ddot{y} = g(\rho - \rho_1)/(\rho + \rho_1) \quad \ldots\ldots (1)$$

as the equation for the vertical component of motion of the centroid of our slice.

By the perfect gas law we may write (1) as

$$\ddot{y} = g(1 - T/T_1)/(1 + T/T_1) \quad \ldots\ldots (2)$$

where T and T_1 are the respective absolute temperatures. The equation of our linear temperature

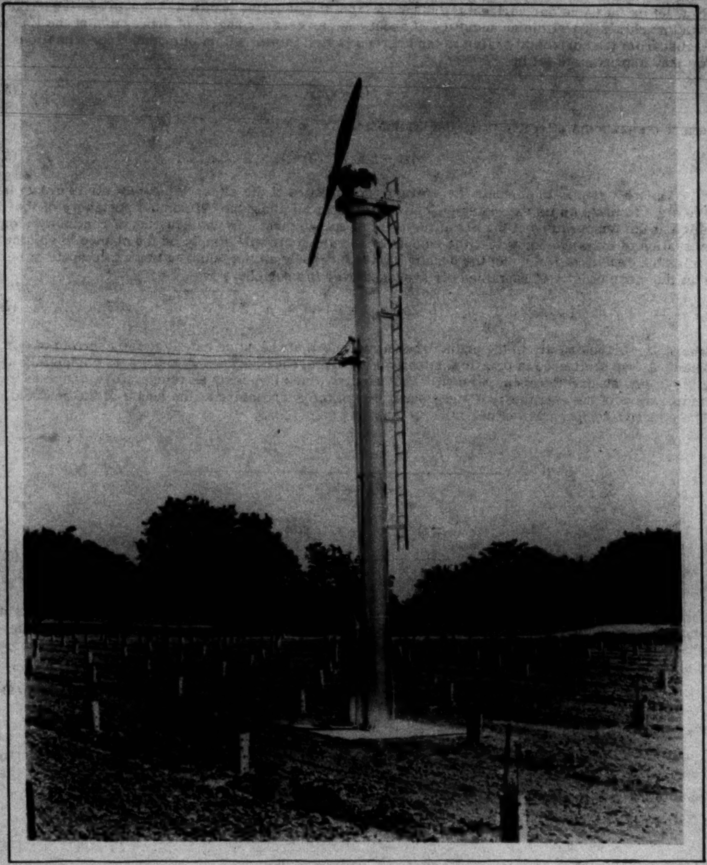

Fig. 1--A common design of wind machine

gradient is

$$T_1 = T_o(1 - \alpha y) \quad \text{(3)}$$

Let s denote the distance, measured along the curve traced out by the motion of the centroid of our slice, then according to our assumptions (this becomes exact as the temperature gradient goes to zero) the radius of our cylindrical slice is given by

$$r = 0.214\ s \quad \text{(4)}$$

Now let us measure our horizontal distance x from the effective position of the propeller of the wind machine. To within an accuracy of about one per cent for angles of depression of the line of thrust from the horizontal of five to ten degrees (which is well within our other approximations), we may approximate (4) by

$$r = d(1 + x/f) \qquad \text{.......................} \qquad (5)$$

where d equals the effective propeller radius and

$$d/f = \tan(24^\circ/2) \qquad \text{.......................} \qquad (6)$$

The next step is to compute the average temperature of the slice. When new air is drawn into the slice to make up its expanding bulk, it is drawn in all along the cylindrical periphery of the slice at the temperature of the air at the point of entrainment. By the equation of continuity (conservation of mass) we know that the amount of entrained air will simply be the change in volume times the density of fluid. As the density varies inversely as the temperature we compute at once that the mean density of entrained air averaged over the periphery is

$$\bar{\rho} = (\rho_c/2\pi)\int_0^{2\pi}[1/(1 - \alpha_c r\cos\theta)]\,d\theta = \rho_c/\sqrt{1 - \alpha_c^2 r^2} \qquad \text{...........} \qquad (7)$$

where ρ_c is the density in the undisturbed atmosphere at the same height as the centroid of our slice. As we shall see, in practical situations the difference between $\bar{\rho}$ and ρ_c is completely negligible (a few hundredths of one per cent). As density varies inversely as temperature, the average temperature of the entrained air must equal that of the surrounding at the height of the centroid. The effective temperature of our slice is thus

$$T = \frac{\pi d^2 T_0^2 + \int_0^x 2\pi T_0 (d^2/f)(1 + x/f)(1 - \alpha y)\,dx}{\pi d^2 (1 + x/f)^2}$$

$$= T_0\left(1 - \frac{(2\alpha/f)\int_0^x (1 + x/f)\,y\,dx}{(1 + x/f)^2}\right) \qquad \text{.....................} \qquad (8)$$

For the purpose of computing the forward progress of our cylindrical slice we make only a slight (and essentially inconsequential for our approximate calculation) error if we assume that the density is uniform throughout. Under this assumption, we have, by conservation of the flow of momentum

$$\dot{x} = \dot{x}_0/(1 + x/f) \qquad \text{.......................} \qquad (9)$$

or, integrating and solving for x

$$x = f\left[(1 + 2\dot{x}_0 t/f)^{0.5} - 1)\right] \qquad \text{.......................} \qquad (10)$$

Substituting (10) in (8) we obtain

$$T = T_0\left(1 - \frac{(2\alpha\dot{x}_0/f)\int_0^t y\,dt}{(1 + 2\dot{x}_0 t/f)}\right) \qquad \text{.................} \qquad (11)$$

Now from (2), (3), and (11) we obtain

$$\left(2 - \alpha y - \frac{(2a\,\dot{x}_0/f)\int_0^t y\,dt}{(1 + 2\dot{x}_0 t/f)}\right)\ddot{y} + g\alpha y$$

$$= \frac{(2g\alpha x_0/f)\int_0^t y\,dt}{(1 + 2\dot{x}_0 t/f)} \qquad \text{.......................} \qquad (12)$$

Let us now consider some values of the constants involved, in order to obtain an approximate solution. From the data of RHOADES and Others [1954], we note that

$$\left.\begin{array}{ll} g = -32 \text{ ft/sec}^2 & \alpha = -5 \times 10^{-4} \\ \dot{x}_0 = 90 \text{ ft/sec} & \dot{y}_0 = -5.2 \text{ ft/sec} \\ f = 30 \text{ ft} & d = 6.5 \text{ ft} \end{array}\right\} \quad \ldots\ldots\ldots\ldots (13)$$

are typical values, where $\dot{x}_0$ and $\dot{y}_0$ are the components of the jet velocity at the effective position of the propeller. Now for t small

$$\int_0^t y\,dt << y \quad \ldots\ldots\ldots\ldots (14)$$

and for t greater than two seconds

$$1/(1 + 2\dot{x}_0\, t/f) < 0.1 \quad \ldots\ldots\ldots\ldots (15)$$

also αy is small compared to 2. Thus, (10) reduces to

$$2\ddot{y} + g\alpha y = 0 \quad \ldots\ldots\ldots\ldots (16)$$

Hence, the trajectory of the centroid is

$$y = [\dot{y}_0 \sin(\sqrt{g\,\alpha/2}\; t)] / \sqrt{g\alpha/2} \quad \ldots\ldots\ldots\ldots (17)$$

This result, although admittedly only an approximation to the actual case of a wind machine in an orchard, is very significant. We see from it that it is the quantity $g\alpha$ which sets the time scale of the wind-machine action and is the important factor on which we can proceed to base a further, more realistic analysis of the problem.

We note that, combining (17) and (11), we find the average absolute temperature of the jet to be

$$T = T_0\left[1 - \frac{4\dot{x}_0\dot{y}_0\,(1 - \cos\sqrt{g\alpha/2}\; t)}{gf\,(1 + 2\dot{x}_0\, t/f)}\right] \quad \ldots\ldots\ldots\ldots (18)$$

For the actual case the other terms will cause the oscillations to damp out. If our stationary jet impinges on a layer of trees, that part of the jet which enters this layer will be greatly impeded by the drag of the leaves and branches. Thus the frost protection action of a stationary jet consists in the transporting of warmer air over the tree tops and then pumping it into the trees, which retain the warmer air for a relatively long time.

Turning jet in an isothermal environment--Let us now consider a jet turning uniformly about a vertical axis in an isothermal environment. Now the horizontal plane containing the jet is a plane of symmetry. In this plane the Z (vertical) component of velocity, w, and dw/dZ must be zero, for if this were not true, then there would not be the required symmetry. Hence, we can treat this problem in the plane itself and bring into play the highly developed theory of functions of a complex variable. For, let us now consider the time average velocity as a function of position. As the velocity is a periodic function of the time

$$\lim_{T \to \infty} (1/T) \int_0^T (\partial v/\partial t)\, dt \to 0 \quad \ldots\ldots\ldots\ldots (19)$$

Hence [LAMB, 1945] the time average obeys the laws of plane flow.

The flow will clearly be radially outward, since the jet imparts no angular momentum to the air. It is well known [LAMB, 1945] that the velocity potential function for such a situation is

$$F(z) = a \log_e z \quad \ldots\ldots\ldots\ldots (20)$$

where a is real and positive. We may evaluate a by considering the flux outward from the jet, which is equal to the imaginary part of

$$F(e^{2\pi i}) - F(e^{0}) = 2\pi a i \tag{21}$$

and equating it to the jet flux, thus

$$a = \text{jet flux}/2\pi \tag{22}$$

The velocity is, of course

$$v = a/z^{*} \tag{23}$$

where * denotes the complex conjugate.

Now if we pass any vertical plane through the jet and take the time average, we again have a plane problem. Here the flow looks like two abutting stationary jets [PRANDTL, 1952, Fig. 3.10, p. 122].

Now let us alter the problem by adding a steady air drift. Without loss of generality we can select our drift to be in the direction of the negative real axis. Hence the new velocity potential becomes

$$F(z) = bz + a \log_e z \tag{24}$$

and the velocity

$$v = b + a/z^{*} \tag{25}$$

where b is real and negative. The lines of flow are given by equating the imaginary part of F (z) to a constant, or

$$by + a \arg z = \text{constant} \tag{26}$$

Mean arrival time for turning jet--Now, if we have a turning jet operating in a linear temperature gradient, the analysis of a vertical cross section proceeds much as in section two, except that the virtual mass is now probably different. It is evident from the discussion of section two that the frost-protection action for a stationary jet must be dependent on the dimensionless parameter

$$\tau = (1/2\pi)(g\alpha/2)^{0.5}\, t \tag{27}$$

This dependence should be most pronounced in the peripheral response zone. Such must also be the case for the turning jet. Consequently, it is of interest to compute the mean time of arrival at any point. We have

$$dt = \frac{ds}{ds/dt} = \frac{ds}{v} \tag{28}$$

and

$$v = \left| F'(z)^{*} \right| = \left| F'(z) \right| = \left| b + a/z \right| \tag{29}$$

$$ds = \left| dz \right| \tag{30}$$

Hence, using polar coordinates in the plane of the turning jet, we have

$$\frac{ds}{v} = \frac{rdr}{a}\sqrt{\frac{1 + r^2\,(d\theta/dr)^2}{1 + 2(br/a)\cos\theta + (br/a)^2}} \tag{31}$$

Now (31) must be integrated along a line of flow (26) given by

$$(br/a)\sin\theta + \theta = C \tag{32}$$

Substituting (32) into (31) we obtain

$$dt = \frac{ds}{v} = \frac{(\theta - C)\, d\theta}{a \sin^2 \theta} \quad (\theta \neq 0^\circ \text{ or } 180^\circ) \qquad (33)$$

and integrating between $\theta = C$ and $\theta = \theta$ we obtain

$$t = (x/b) + (a/b^2) \log (\sin \theta / \sin C) \qquad (34)$$

with

$$C = \theta + by/a \qquad (35)$$

Taking the limit as θ tends to 0° or 180° we obtain

$$t = (x/b) - (a/b^2) \log (1 + bx/a) \qquad (36)$$

or

$$t = x^2/a, \text{ if } b = 0 \qquad (37)$$

for the on-axis-time.

Deadspot determination--Now, to compute the thermal response, we must consider the retentivity of the warm air by the trees. The effect of this factor is to increase the size of the pattern out to about the utmost point of wind machine effect; it gives us effectively a larger wind machine. Hence if the period of rotation is not long compared to the retention time (which seems to be the case with current operating procedure), to compute this response pattern we use the time average velocity of a larger wind machine with constant a' such that $-a'/b$ equals the distance to the up wind deadspot of the original machine.

In order to determine this deadspot we must find an expression for the effective velocity, v_t, of the turning jet. This velocity will, as has been remarked before, be radial. It is easy to show that, in order to be dimensionally correct [LANGHAAR, 1951] this expression must be of the form

$$v_t = (K/r)(F/\rho)^{0.5}\, f(r^2 \omega\ (\rho/F)^{0.5}) \qquad (38)$$

where F is the thrust; ρ, the density of the air; ω, the angular frequency of turning; r, the distance from the jet; K, a constant; and f, a yet undertermined function with $f(0) = 1$. By setting $\omega = 0$, we can determine K from the stationary jet formulas. It is [LEONARD, 1953]

$$K = 5.5 \qquad (39)$$

Now when r is very large ($\omega \neq 0$) the flow approaches that of (23) and

$$v_t = (0.25/r)\sqrt{F/\rho} \qquad (40)$$

Thus, we must have

$$v_t = (5.5/r)(F/\rho)^{0.5}\left[(1/22) + (21/22)\, h\, (r^2 \omega\ (\rho/F)^{0.5})\right] \qquad (41)$$

with

$$h(0) = 1,\ h(\infty) = 0 \qquad (42)$$

If we select

$$h(x) = e^{-0.40x} \qquad (43)$$

then we obtain a function whose agreement with observation [LEONARD, 1953] is within the experimental error. (It is an interesting conjecture that the 0.40 of (43) is in fact $\gamma - 1$, where γ is the ratio of specific heats of the gas (air).) Hence, the deadspot, D, is determined by

$$-b = (5.5/D)(F/\rho)^{0.5}\left[(1/22) + (21/22) e^{-0.40 D^2 \omega\ (\rho/F)^{0.5}}\right] \qquad (44)$$

The average time of arrival is more significant than the actual time because of the strong averaging effect of the trees and its closer connection with the heat transport.

Peripheral thermal response of a turning jet--By the use of the data taken by Rhoades and Others 2/8-9/54, 2/10-11/54, and 2/11-12/54 in citrus orchards, the following relation has been roughly established

$$\Delta T = 2.52/(\tau)^{4/5} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (45)$$

or

$$\Delta T = 2.52\left\{(1/2\pi)(g\alpha/2)^{0.5}\left[(x/b) + (a'/b^2)\log_e(\sin\theta/\sin C)\right]\right\}^{-4/5} \quad \ldots\ldots (46)$$

$C = \theta + by/a'$ and a'/b determined by section five, where ΔT is the thermal response at a point. The above relationship appears to hold as long as the isotherms encircle the wind machine. For the large wind machines investigated (around 1000 pounds thrust), (46) holds for ΔT up to about 35 pct of the difference in temperature between the air at the height of the wind machine (about 40 ft) and that in the orchard.

Multiple settings--The next question that comes to mind pertains to possible advantages of multiple settings. We shall consider the average flow velocity of one of the simplest multiple settings, an infinite square lattice of turning wind machines of equal flux. The velocity potential will be essentially the sum of the separate velocity potentials. Thus, adding and subtracting the appropriate quantities from each term to make an absolutely convergent series, we obtain

$$F(z) = a\log_e\sigma(z) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (47)$$

where $\sigma(z)$ is Weierstrass' sigma function [COPSON, 1948]. The velocity is now

$$v = a\zeta(z)^* = a\left[(1/z) + \sum_{m,n}\left(1/(z - c(m + in)) + 1/c(m + in) + z/c^2(m + in)^2\right)\right]^* \quad \ldots (48)$$

where $\zeta(z)$ is Weierstrass' zeta function and c is the distance between wind machines. Now $\zeta(z)$ has the following properties

$$\left.\begin{array}{ll} \zeta(z + c) - \zeta(z) = 2\,\zeta(c/2) & \\ \zeta(z + ic) - \zeta(z) = 2\,\zeta(ic/2) & \\ \zeta(c/2) = \pi/2c & \zeta(ic/2) = -\pi i/2c \end{array}\right\} \quad \ldots\ldots\ldots\ldots\ldots (49)$$

By (48) and (49) we see

$$\left.\begin{array}{l} v(z + c) - v(z) = \pi a/c \\ v(z + ic) - v(z) = \pi ia/c \end{array}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots (50)$$

Thus, we see that the difference between the pattern of one wind machine and the next is something like the superposition of a radial wind of magnitude

$$\pi ar/c^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (51)$$

In a general two-dimensional lattice of wind machines the same effect will exist, except, of course, there will not be the radial symmetry of the square lattice. As the driving force behind this effect in the square lattice is the outward flux of the wind machines nearer the center of the pattern, in a finite setting we expect the same effect. Let n (K) be the number of wind machines interior to an orthogonal trajectory, K, of the curves of flow, and L (K) be the length of K. Hence, by Cauchy's theorem, the average outward velocity across K, $\bar{v}$, is

$$\bar{v} = 2\pi n(K)\, a/L(K) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (52)$$

or, if $2\pi a_k$ is the flux of the k^{th} machine

$$\bar{v} = [2\pi/L(K)] \sum_{k=1}^{n(K)} a_k \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (53)$$

If we now consider a distribution of infinitely many, infinitely small wind machines forming a square lattice so that there exists a uniform density of wind machines, then

$$\left.\begin{aligned} an(K) &= \pi \rho_w r^2 \\ L(K) &= 2\pi r \end{aligned}\right\} \quad \text{.......................} \, (54)$$

Therefore

$$\bar{v}(r) = \pi \rho_w r \quad \text{.........................} \, (55)$$

If this pattern is located inside a circle of radius R, then, for a single wind machine of the same total flux, we have

$$v(R) = \pi \rho_w R \quad \text{.........................} \, (56)$$

The flow pattern outside R is the same for the two setups but inside it is clearly much different.

Summary and discussion--In the second section of this paper the frost protection action of a stationary jet in the absence of wind is studied. The response pattern does not end for τ around one-half as might be expected, for the cone spreads more rapidly than it rises and the barrier of the trees and the ground causes an elongation of the pattern. One cannot, of course, use (18) to predict the thermal response since the temperature distribution in the jet is far from uniform and the presence of the trees alters the flow.

In the third section we study the time average pattern of a uniformly turning jet, with and without wind. It seems to be the time average pattern that is important because the result desired in frost protection is the average temperature of the fruit. The analysis of this section is exact and fairly simple formulas are developed to describe the time average flow of the uniformly turning jet. A problem for further investigation would be that of the non-uniformly turning jet.

In the fourth section we derive an expression for the mean time of arrival of air from the wind machine to any point, and the dimensionless parameter τ is introduced. In the fifth section we work out a semi-empirical formula for the velocity of a turning jet. It is unfortunate that there are no observations [LEONARD, 1953] for the region of particular interest to us.

In the sixth section we present an empirical relationship between temperature response and other measurable physical quantities. We know from the work of sections two through four that there must be some such relationship, and this one is probably not too far off, even though it has such a scant experimental foundation. The region of validity is, as yet, not too well defined. The down pitch angle is about a normal setting (five to ten degrees). For small machines the minimum angle would be larger than for the big machines. In any case it should be sufficient to insure the penetration of the jet centroid into the trees (see (17)). The thrust of the machine undoubtedly influences the region of validity but I think that, in most cases of practical interest, the important two-degree isotherm would be included in it. These results appear to be in reasonable accord with the data of RHOADES and Others [1954], but the restricted region of validity of (46) and the crudeness of the data limit the possibility of cross checking.

In the final section we investigate the flow pattern of multiple settings, in particular, an infinite square lattice of uniformly turning jets. The derivation of certain general formulas puts on a fairly quantitative basis the fact that two wind machines are better than twice as good as one wind machine of the same flux; however, it is doubtful that they are better than one wind machine of double the flux, where, of course, the flux is proportional to the square root of the thrust. These results should be very useful in the selection of the economically optimum size for wind machines and in the resolution of the problem of multiple settings versus single settings.

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ON THE OFFSHORE CIRCULATION AND A CONVERGENCE MECHANISM IN THE RED TIDE REGION OFF THE WEST COAST OF FLORIDA

Frank Chew

Abstract--The offshore water is shown to move as a single column. The sloping bottom and the equation of continuity are then applied to show the existence of a horizontal convergence mechanism which, over a period of several weeks, may effect a several-fold increase in concentration of floating particles. The southbound current in the 'loop' is thought of as a Rossby jet which drives the cyclonic eddy offshore. Consideration of the abbreviated vorticity equation, together with the fact of sloping bottom, show that the southeastern quadrant of the cyclonic eddy possesses increasing negative vorticity and hence the organisms previously concentrated will tend to wash ashore. Some consideration of the effects of wind are also included.

Introduction--The sporadic blooms of Gymnodinium brevis (an unarmored dinoflagellate) causing mass mortality of marine animals off the west coast of Florida are popularly known as the 'Red Tide.' Observations during the Red Tide bloom of 1946-47 showed that patches of dead fish some several to tens of miles in horizontal dimensions were of frequent occurrence. Thus GUNTER and Others [1948] wrote, " ... the captain of a small freighter... sailed through dead fishes from Dry Tortugas to Ft. Myers... the disturbace was many miles farther offshore at the southern end of the Florida peninsula than at its northern limits." Again, Gunter related that the surface of the ocean north of the Florida Keys was reported to be covered with dead fish. During the briefer outbreak of Red Tide in 1952, the St. Petersburg Times reported that there were "... millions of dead fishes from Dry Tortugas to Ft. Myers." During the Red Tide bloom in 1954, a Coast Guard seaplane summoned on July 24 by the Gulf Coast Coordinating Committee (a voluntary group organized to help in Red Tide researches) to investigate fishermen's reports, found a large but thin patch of dead fish 15 to 30 mi offshore and measuring several miles wide and upward to many times that long.

The large horizontal dimensions of these patches of dead fish preclude the phenomenon from being oversized windrows or resulting from causes related to the wind [STOMMEL, 1951]. Surface convergence after the manner of the Sargasso Sea is not possible as there exist no corresponding wind systems. Yet a convergence mechanism must exist. A good portion of the present paper explores the possible role here of bottom topography in a convergence mechanism.

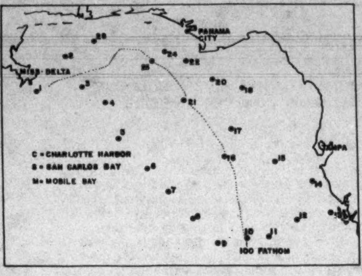
The observed outbreaks of Red Tide at beaches generally show a sequence of south to north movement. Thus, GUNTER and Others [1948] reported, "The (Red Tide) mortality moved northward and shoreward and reached the bays behind Sanibel and Captiva Islands."

The remaining portion of this paper discusses the offshore circulation in an attempt to find the mechanics of the northward and shoreward movement.

The water masses and their circulation--The offshore observations used in this paper were made by the Texas A and M Department of Oceanography during Cruises 3-1C and 3-2C in the periods August 10-21, 1951, and May 30 to June 3, 1952, respectively. Since the pertinent results of both cruises are essentially the same, only the data of Cruise 3-1C [TEXAS A and M, 1952] will be analysed in detail in this paper.

Figure 1 gives the station locations and Figures 2 to 5 the salinity patterns at several depths from the surface to 150 m; Figure 6 gives the temperature pattern for the 20-m depth. The horizontal salinity field becomes more uniform with depth so that the isohalines were drawn at smaller intervals at greater depths for clearer definition of the field.

The salinity of the water will be used as a tracer for its movement. This is reasonable for the area of interest, as the sources of the major waters are known and, since the geostrophic state is not assumed, water may cross lines of equal salinity.


PANAMA CITY
MISS. DELTA
TAMPA
C = CHARLOTTE HARBOR
S = SAN CARLOS BAY
M = MOBILE BAY
100 FATHOM
1
2
3
4
5
6
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25
26

Fig. 1--Station locations

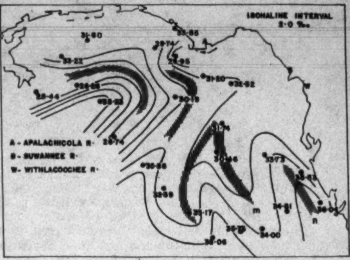

ISOHALINE INTERVAL 2·0 ‰
A - APALACHICOLA R.
S - SUWANNEE R.
W - WITHLACOOCHEE R.
W
m
n
31·60
32·22
28·44
30·19
31·20
32·62
35·06
34·00
35·01

Fig. 2--Surface salinity distribution

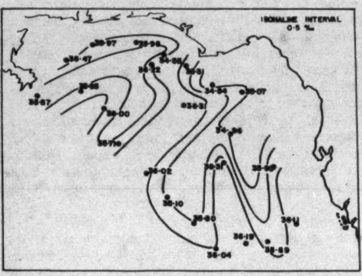
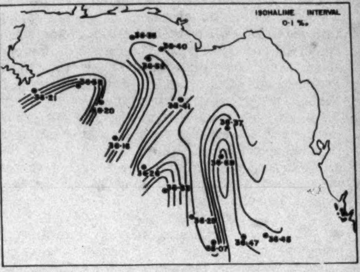

ISOHALINE INTERVAL 0·5 ‰
36·47
36·67
36·00
36·02
36·10
36·04
36·07
36·31

Fig. 3--20-meter depth salinity pattern


ISOHALINE INTERVAL 0·1 ‰
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36·20
36·40
36·47
36·45
36·07

Fig. 4--50-meter depth salinity pattern

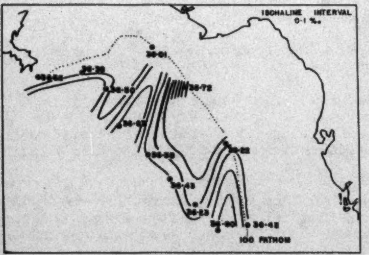
ISOHALINE INTERVAL 0·1 ‰
36·01
36·72
36·42
100 FATHOM

Fig. 5--150-meter depth salinity pattern

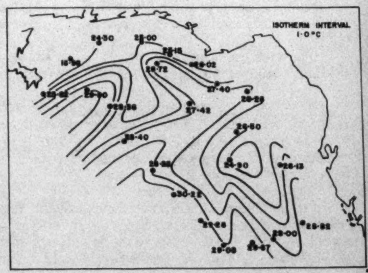
ISOTHERM INTERVAL 1·0 °C
25·00
27·40
27·42
28·60
26·15
30·22
28·00
29·06

Fig. 6 --Temperature at 20 meters

Three, and possibly four, major water masses and their respective sources may be identified from Figure 2 which depicts the surface distribution of salinity. The first and most obvious is the Mississippi estuarine water which has its source in the Mississippi drainage system. The second is the Florida west coast estuarine water which has its primary sources in the estuaries of Apalachicola in the north, Suwannee, Withlacoochee, Tampa, Charlotte, and San Carlos in the west. The third water mass is what may be called the 'loop-current water mass' which has its source in the warm, saline current flowing north through the Yucatan Channel and into the Gulf of Mexico before its return south to join the Florida Current. A possible fourth water mass is the Florida Bay water mass, with its source in Florida Bay and the shoal regions north of the Florida Keys.

Figure 7 presents the temperature-salinity correlation curves for several selected stations. The first point on each curve is the surface T-S value, while each successive point represents the T-S values at the depths of 10, 20, 30, 50, 75, 100, and 150 m. In every case, the last point plotted represents that for 150 m. The inset is an enlargement for greater clarity along the salinity coordinate for selected stations.

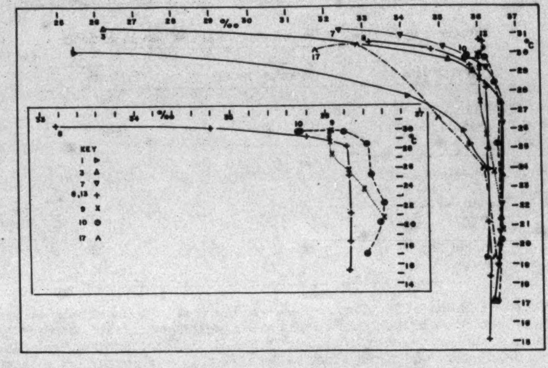

Fig. 7--Temperature-salinity correlation

Taking Stations 1 and 17 as representative locations in the Mississippi and the Florida west coast estuarine waters respectively, one sees in Figure 7 that the former water mass can be traced to a greater depth than the latter; hence the T-S characteristics of the first 50 m of water at Station 1 and that of the first 30 m at Station 17 will be taken to define these respective waters. These values are given in Table 1. The Florida Bay water was not well sampled, but for the present purpose, the data at Station 13 may be used. The loop-current water appears at a depth greater than 30 m at Station 3, 50 m at Station 7, 150 m at Station 9, and 30 m at Station 10; at these depths the salinity is bracketed within the narrow range of 36.4-36.6 ⁰/oo.

The high upper temperature limits of the two estuarine waters are primarily the results of boundary influences. It is instructive to compare the T-S characteristics of the four water masses at a depth approximately below the thermocline at the same stations enumerated above. The 20-m depth has been chosen for this purpose and the respective T-S values are given in Table 2.

It can be seen that at this depth the estuarine waters are colder and fresher than that of the loop current. This is readily understood as being the result of continual advection of warm and saline water in the loop current. The relatively high temperature and salinity characteristics of the Florida Bay water are more difficult to explain on the basis of present data. But, fortunately, previous work done by this Laboratory indicates that the Florida Bay and the shoal area north of the Florida Keys act, in the summer, as a giant evaporation pan where salinity may be as high as 37.0 ⁰/oo and temperature 30°C or more.

Table 1--Range of T-S characteristics of the water masses

Water mass	Temperature	Salinity
	°C	‰
Mississippi estuarine water	24.0 to 30.0	25.5 to 36.2
Florida west coast estuarine water	24.0 to 30.0	28.9 to 36.1
Loop-current water	17.0 (150 m temperature) to 28.5	36.4 to 36.6
Florida Bay water	30.5	36.1

Table 2--T-S values of the water masses at the 20 m depth

Water mass	Temperature	Salinity
	°C	‰
Mississippi estuarine water	26	35.6
Florida west coast estuarine water	25	35.0
Loop-current water	30	36.0
Florida Bay water	29	36.1

The offshore circulation--The circulation pattern inferred from the salinity distribution is remarkable in its similarity to the surface drifts of the September current charts of the Central American Waters published by the Hydrographic Office (H. O. Misc. 10690 series). The poorer agreement with the August current chart may be the result of the averaging out of significant details in the preparation of the H. O. chart, or it may be the result of early seasonal change of current patterns. Parts of the August and September charts are reproduced here as Figures 8 and 9.

The Mississippi estuarine water does not appear to mix with the Florida west coast estuarine water. Their separate identities appear to be insured by the presence of the northeast 'intrusion' of the loop current which swings cyclonically toward Panama City and west. The proof of the existence of this intrusion is predicated on the consideration that since the relatively high salinity values at Stations 2, 28, 24, and possibly 23 must be maintained against the diluting effect of nearby estuarine waters, there must be a continual salt replenishment, which on this scale can be effected only by advection or upwelling. The upwelling process is ruled out as improbable, for, as will be seen in the next section, the horizontal salinity patterns at all depths indicate water movement in the same general direction at all depths. That the relatively high salinity values observed at the several stations mentioned are more or less a permanent feature is indicated by the surface salinities obtained by RILEY [1937] and by AUSTIN [1954] who, in his study of Mobile Bay in October 1952, found Gulf water salinities to exceed 34 ‰ at the late flood stage at the main pass. It is true that the sheltered shoals along this section of the shores of the Gulf of Mexico often generate water of high salinity in the summer, [INGLE and DAWSON, 1953]; their volumes, however, are limited and cannot be considered as sources of the high saline water offshore.

The eastward movement of the Mississippi estuarine water and the northeast 'intrusion' of the loop-current appear to be integral parts of a cyclonic eddy. The eastern movement of the Mississippi estuarine water is of interest in view of LYNCH's [1954, p. 76] statement, "It is a generally accepted fact that water discharged from the Mississippi River is carried almost entirely to the west..."

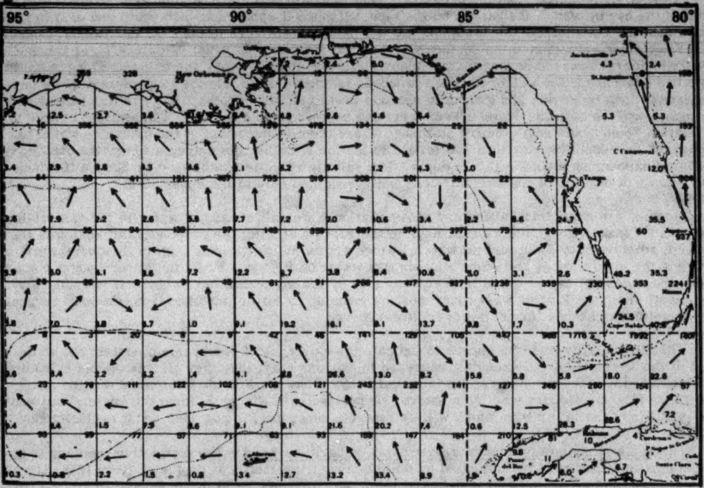
95°
90°
85°
80°
New Orleans
Jacksonville
St. Augustine
C Canaveral
Tampa
Cape Sable
Havana

Fig. 8--Current chart, August, H. O. 10690-8

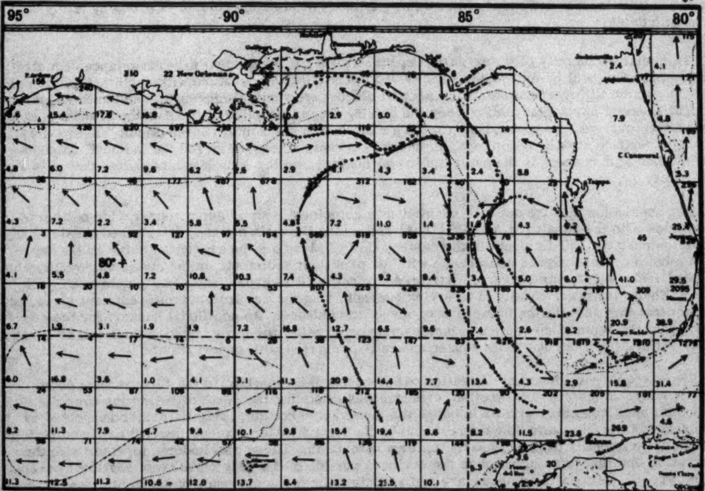
95°
90°
85°
80°
New Orleans
Jacksonville
C Canaveral
Tampa
Cape Sable

Fig. 9--Current chart, September, H. O. 10690-9

During the summer when the prevailing wind is easterly the Apalachicola estuarine water leaves the bay by way of the passes on the west; offshore it appears to turn south and east to join the estuarine waters from the Suwannee and Withlacoochee Rivers to the east and Tampa, Charlotte, and San Carlos estuaries to the southeast. Then the Florida west coast estuarine water takes a cyclonic course towards deeper bottom where, near the 100-fm depth, the estuarine tongue splits into two branches. The western branch proceeds farther west to join the loop current while the eastern branch turns SSE and gradually ascends toward shallow depths. The reality of these two branches and the salinity ridge between them can be seen from Figure 7. The western branch turns at Station 7 and heads south toward Station 8, where the diluting effect of the estuarine water can be traced to a depth greater than 150 m, and to Station 9 farther downstream where the diluting effect is disappearing near the 150-m depth. The salinity ridge is established by Station 10 where the volume of dilution is considerably less and is confined only to the upper 30 m.

Previous work by this Laboratory shows that only a small amount of water in the eastern branch appears to 'leak' through the Florida Keys to the Florida Straits; the preponderant portion of the branch, reinforced by loop-current water, swings around in its cyclonic path to flow northward, entraining the highly saline and warm Florida Bay water on its way. From the water-budget point of view, the excess of export out of the cyclonic eddy by the western branch over that introduced by the runoff along the Florida west coast must be made up by water imported from the loop current; the magnitudes of these terms, however, are unknown.

Thus the salinity patterns appear to indicate the existence of two cyclonic eddies: one to the east of the Mississippi and extending eastward to Panama City; the other off Tampa and extending westward to the 100-fm contour. The northward flow along the Florida west coast and the southward flow farther offshore labelled n and m, respectively, in Figure 2, form the eastern and western portions of the latter eddy which will be referred to as the Florida west coast cyclonic eddy.

The depth of no-motion (depth of horizontal isobaric surface)--The distinctive features of the surface salinity pattern are duplicated by the temperature patterns at depths of 20-m (Fig. 6) and greater, and also by the salinity patterns at all depths to at least 150 m, or essentially to the bottom of the water columns for stations east of the 100-fm contour. That is, over the shallow continental shelf, the water columns appear to move as a unit and, except for boundary friction at the top and bottom layers, the speed of the water particles within each column is probably fairly uniform with depth.

This near uniformity of water-parcel speed, with depth, may appear to be at variance with stratification brought about by increasing salinity and decreasing temperature with depth within the column. A column with vertical stratification will discourage vertical movement and hence encourage vertical shear of horizontal motion when the driving force is applied at the surface boundary, as in wind-driven current. However, body forces giving rise to horizontal motion do not, essentially, vary with depth in stratified columns, as in tidal current. Thus, while, for the moment, no postulate is made with respect to the nature of the acting force on the eddy it can be stated that it is a body force.

The conclusion that the depth of no-motion is coincident with or below topographic bottom is in consonance with the results of ADAMS [1954] who, using Defant's method, determined the depth of no-motion near the 100-fm depth in the eastern Gulf of Mexico to be nearly the same as the topographic bottom. It is also in consonance with the prevalent sediments on the continental shelf, which are hard rocks with a thin veneer of detrital sediment in local areas, and coral patches, LYNCH [1954]. There are many pitfalls to inferring current along the sea bottom from sediment sizes, but it is felt that this association is more than mere coincidence. An additional support for the conclusion that the depth of no-motion coincides with or is below the topographic bottom will be given in the next section when one of its consequences is compared with observation.

A convergence mechanism--Attention will henceforth be confined to the Florida west coast cyclonic eddy. In the previous section, evidence was cited that the depth of no-motion over the continental shelf coincides with or is below the topographic bottom. This is further supported by the absence of sizable basin-like depressions in the bottom. Also, except for wind drift and bottom friction, the current is probably nearly uniform with depth. These conclusions, together with the observation that the water columns in the northern portion of the eddy move from shallow to deeper bottom, are all the conditions necessary and sufficient for the occurrence of horizontal convergence, for, as the total depth of the column increases, there must be convergence. This can readily be seen by considering the principle of mass conservation as one follows the movement of a typical column

$$DM/Dt = (D/Dt)\ (\rho hA) = 0 \tag{1}$$

where the operator D/Dt is the time change following the individual column and where h is the total depth of the water column, A is the horizontal area of the water column, M is the total mass within the column, and where, as usual, the change in the density, ρ, of the water within the column has been neglected. From (1)

$$hA = (hA)_0 \tag{1a}$$

that is, the volume of the column at a later time is the same as that initially. Again from (1),

$$(1/h)\ Dh/Dt = -(1/A)\ DA/Dt \tag{1b}$$

The left-hand term in (1b) may be written

$$(1/h)\ Dh/Dt = (1/h)\ (\partial h/\partial t + u\ \partial h/\partial x + v\ \partial h/\partial y) \tag{2}$$

Since h is also the depth of the topographic bottom, h is not a function of time, t. And for the purpose of this section, $\partial h/\partial y$ is taken as zero, so that equation (1b) becomes

$$(1/A)\ DA/Dt = -(u/h)\ dh/dx \tag{3}$$

This equation states that the amount of horizontal convergence is dependent on the steepness of the continental shelf and the speed of the water column. If the bottom topography contains a series of shallow depressions so that dh/dx changes sign there will be zones of greater convergence separated by areas of divergence or lesser convergence. This is schematically illustrated in Figure 10.

In stratified columns, generally, a consequence of horizontal convergence into the columns as they move toward deeper bottom is an increasing thickness of the upper layer of lighter water. Available evidence on this point is very suggestive. The ten-meter temperature pattern (not reproduced) shows the temperature at Station 11 to be greater than those at Stations 12 and 15; and the pattern at the 20-m depth (Fig. 6) shows the temperature at the same Station (11) to be higher than those at Stations 15 and 17. LEIPPER and ADAMS [1951, Fig. 2] showed average temperature curves with approximately the same feature.

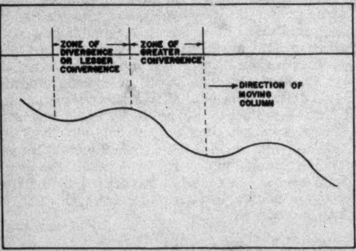
ZONE OF DIVERGENCE OR LESSER CONVERGENCE
ZONE OF GREATER CONVERGENCE
DIRECTION OF MOVING COLUMN

Fig. 10--Convergence and bottom contour, a schematic illustration

The order of magnitude of horizontal convergence due to a uniform sloping bottom may be estimated as follows:

Let

$$h = ax \tag{4}$$

where a is a constant;
then

$$(u/h)\ dh/dx = u/x \tag{5}$$

For

$$u = 1 \text{ nautical mi per day}$$
$$x = 10 \text{ n mi or } 60{,}000 \text{ ft} \tag{6}$$

then

$$(u/h)\ dh/dx = 0.1\ \text{day}^{-1} \tag{7}$$

Or from (3)

$$DA/Dt = -(A/10)\ \text{day}^{-1} \tag{8}$$

That is, the horizontal area of the typical water column at 10 mi offshore is decreasing at the rate of 0.1 of its area per day as the column moves toward deeper bottom at a speed of one nautical mile per day. To show the accumulated decrease in horizontal area as the column goes seaward, (1a) is used. If (4) is substituted in (1a) there results

$$A/A_0 = x_0/x \tag{9}$$

The column at ten miles offshore will be taken as the reference column, so that t = 0 corresponds to the 10-mile position, and since Dx/Dt = u, then x = ut + 10 if u is constant over the interval of interest; hence

$$A = A_0\ [10/(10 + ut)] \tag{9a}$$

If u is one nautical mile per day, then in ten days the original area A_0 will be reduced to one-half, and in 40 days to-one-fifth.

For a second estimate of the order of magnitude of convergence let

$$h = ax + b \sin (2\pi/L)\, x \quad \ldots\ldots (10)$$

where b is another constant.

This is an expression for a uniform sloping bottom with a series of symmetrical ridges and depressions superposed. Then

$$(1/h)\, dh/dx = [a + (2\pi b/L) \cos (2\pi/L)\, x]/[ax + b \sin (2\pi/L)\, x] \quad \ldots\ldots (11)$$

Maximum and minimum values of (11) are found at $x = nL$ and $x = (n + 0.5)L$ respectively, where n is any integer. For a maximum value in (11) let

$$\left.\begin{array}{l} L = 10 \text{ n mi} \\ n = 1, \text{ or } x = 10 \text{ n mi} \\ b = 3 \text{ ft} \\ a = 30 \text{ fm}/100 \text{ n mi, or } 5 \times 10^{-4} \end{array}\right\} \quad \ldots\ldots (12)$$

then

$$(1/h)\, dh/dx = 2.7 \times 10^{-5} \quad \ldots\ldots (13)$$

If u is one nautical mile per day, then

$$(u/h)\, dh/dx = -(1/A)\, DA/Dt = 0.16 \text{ day}^{-1} \quad \ldots\ldots (14)$$

or about one and a half times the magnitude of (7).

Application of the horizontal convergence mechanism to the Red Tide region--No actual measurement of the magnitude of u, the speed at which the water column traverses from shallow to deeper bottom, has been made. If u is comparable to the net surface drifts given in the current charts of the Central American Waters series of the Hydrographic Office (H.O. no 10690, 1 to 12) then the constants in (6) and (12) may be used. As the assumed magnitude of u is small, it is quite reasonable for it to remain relatively constant over a period of several weeks as the distance covered will be less than 50 mi. In this case, for a uniform sloping bottom, it has been shown that organisms or detritus floating in an area ten miles offshore, say, of 100 sq mi initially will be concentrated to an area of 33 sq mi at the end of three weeks and to 20 sq mi at the end of six weeks as the column flows toward deeper water, provided, of course, that diffusion effect is negligible. These rates of concentration compare favorably with the high total phosphorus content of waters containing the Red Tide organisms as observed by KETCHUM and KEEN [1948] who found it to be from 2.5 to 10 times the maximum to be expected in the sea at stations located from one to five mi off Sarasota Key, with the highest concentration at the five-mile station. The observations reported by CHEW [1953] show comparable concentrations some ten miles offshore south of San Carlos Bay. Of course, if u is larger the time necessary for a given concentration will be reduced.

The rate of horizontal convergence is certainly locally increased by the presence of shallow depressions and ridges of the order of magnitude of less than a fathom. It has been shown that for such topographic features of amplitude of only three feet (12), the concentration rate was increased by 60 pct.

What has been said with respect to horizontal convergence in the x direction applies equally to convergence in the y direction. When convergence in the two directions are in phase, patches of floating non-swimming organisms and other detritus denser than usual will be obtained, other factors being equal. However, this does not mean that such patches will be found wherever there are favorable topographic bottoms. Obviously, their presence depends on the initial supply of organisms.

As these floating patches are carried by the water columns toward deeper bottom, they are, at the same time, flowing away from shore. If some of these patches were to be found later on beaches there must have been a return flow. This will be discussed in the following sections.

A theory of the dynamics of the offshore circulation--The circulation over the continental shelf off the Florida west coast is shown by the current charts of the Central American Waters series mentioned earlier to be present, with some modification, throughout the year. The circulation is most probably not directly wind-driven since FRANCESCHINI [1953] found no apparent relation between the mean wind stress and the mean current in this region. It is perhaps equally improbable that the circulation is primarily one of thermohaline, for the area of interest is limited and shallow, so that considerable frictional forces must be overcome by the force resulting from mass distribution. The juxtaposition of the cyclonic eddy to the 'loop' in the current which on the average flows north from the Yucatan Channel into the Gulf of Mexico and then south through the Florida Straits, suggests that the relatively swift southbound current in the loop may play the role of a jet in the sense of ROSSBY [1936]. In this model a steady stream moving through a resting fluid entrains water from the environs into the stream. Whatever the entrainment mechanism, the depth of no-motion in the southbound loop current is deep enough to entrain the whole water column from the continental shelf, as shown by the dilution effects of estuarine water at Station 8 and 9 in Figure 7, and as indicated by ADAMS [1954]. Individual columns nearer shore are then accelerated by gravity down the sloping bottom of the continental shelf.

One may suppose that the water over the continental shelf is initially at rest and that suction is applied by the southbound loop current, assumed steady for the present discussion. The water over the shelf would then move toward the loop current; columns near the loop current would be dragged by friction into the loop, while columns nearer shore would then be accelerated by gravity and flow down the slope of the continental shelf to replace the entrained columns. The actual entrainment is clearly indicated in the salinity patterns at all depths. If the eastern boundary of the southbound loop current is taken to be located at the 100-fm contour, then roughly one-half of the water from the continental shelf appears to be entrained and absorbed into the loop current while the remainder turns SSE and continues its cyclonic path. From the standpoint of the water budget over the continental shelf, there must be a comparable discharge from the loop current onto the shelf; this is also suggested by the fact that the total depth and position of the eastern edge of the southbound loop current do not appear to change downstream. The discharged loop-current water, mixing with, and so diffusing its momentum into, the estuarine water, appears to furnish the motive power for the southern half of the cyclonic eddy.

Thus it appears that the cyclonic eddy over the shelf is frictionally driven by the southbound loop current with entrainment and compensatory detrainment as the driving mechanism.

The vorticity of the water columns--The vorticity of the water columns in the northern portion of the cyclonic eddy is different from that in the southern portion. It will be seen that this difference may account for the tendency of Red Tide debris to wash ashore. The vertical component of relative vorticity of the column is given by eq.

$$D\xi/Dt = (\xi + f)(1/h)\,Dh/Dt - (2\,\omega \cos \phi)\,(v/r) \qquad (15)$$

where

D/Dt is the operator following the column
h is the height of the column, or the depth of the sea bottom
ξ is the vertical component of the relative vorticity
f is the Coriolis parameter
ω is the angular velocity of the Earth
ϕ is the latitude
r is the radius of the Earth
v is the northern component of the velocity of the water column

and where the torques due to pressure, wind and other frictional forces have been neglected.

The first term on the right in (15) is positive as the water column moves from shallow to deeper bottom, as is the second term on the right when the column turns southward. If one assumes the column to be initially at rest with the Earth, and hence with zero relative vorticity, then, on being entrained into the southbound loop current, the column acquires an increasing net amount of positive vorticity. The water column which was drawn toward deep water but was not entrained will have its positive vorticity increased by the water discharged by the loop current; this vorticity, manifested at least partially in terms of cyclonic curvature, and aided by the contour of the land, will send the column on a counter-clockwise course toward shore. As the shoreward column traverses from deep to shallow bottom, the first term on the right of (15) is negative, as is the second term, as the column turns northward. The positive vorticity acquired earlier by the water column is now being rapidly depleted and is soon replaced by negative vorticity. A water column with net negative relative vertical vorticity will tend to take a clockwise course, in this case, toward shore. If the column has buoyant organisms or detritus suspended in it, they will tend to float onto the beaches. The shoreward tendency during a Red Tide bloom was noted earlier by CHEW [1953] who concluded that high total phosphorus waters were advected toward shore from the open Gulf; the work of KETCHUM and KEEN [1948] is also of significance in this respect, since their highest observed total phosphorus was found at their farthest offshore stations. Additionally the H. O. current chart series mentioned earlier supports this conclusion, as the mean current vectors along the shore in question are shown not parallel to the shores but at an angle toward them. However, as the shoreward column proceeds from deep to shallow bottom, it diverges horizontally; there is a tendency, then, for existing floating patches to spread out, reverting to the distribution before concentration. But the tendency does not necessarily prevail; it is partially offset by at least three physical factors. The first factor is suggested by the observation that the converged detritus or organisms are gathered into individual, small but dense patches separated by varying expanse of low concentration. Most probably, the significant effect of the horizontal diverging current, which is not uniform in space because of 'irregularities' in the topographic bottom, is to transport the separate dense patches away from each other rather than to thin out each and every patch. The second factor is the probability that the shoreward water column may, on occasion, take such a path over the bottom that no significant divergence is experienced until it is some ten to twenty miles offshore, when the increasing negative vorticity of the column directs it toward shore. As the column moves toward shore, now more nearly along the steepest gradient in the bottom slope, there will be considerable divergence; but, by then, the thinning effect of divergence on the patches of organisms is cancelled, in part, by the nearness of land. The third factor is the possible tendency of the shoreward column to move into shallow water as a truncated column, in contrast to movement as a single unit-column when being entrained; for while the latter is acted on by a body force during its seaward journey, the former is not. Consequently, there will be a tendency for greater shearing motion within the shoreward column, resulting in a lesser need for divergence due to change in column height. In total, the net tendency is for thinner but definite patches of floating concentration in the shoreward water columns.

Some effects of the winds--From consideration of water movements alone, the pattern has been derived: that during periods of Red Tide bloom the horizontal convergence inherent in the movements of water columns toward the open Gulf will concentrate floating (or weakly-swimming) Red Tide organisms or detritus into large and dense patches offshore. Some of these patches will be lost to the loop current, but some will return toward shore. As the shoreward columns bearing Red Tide patches acquire increasing negative vorticity, there will be a tendency for these patches to beach ashore anywhere along the Florida Keys and the lower half of the west coast. These patches will be thinner and more widely separated than those found in the converging columns.

Under certain circumstances the winds can aid or modify this pattern considerably. An obvious example is a moderate, steady offshore wind which will certainly keep the Red Tide patches from beaching on shores; an equally obvious example is a moderate, steady onshore wind. It is a matter of observation that when such wind regime prevails during Red Tide bloom, severe Red Tide conditions are found along the coast. Apparently, the dense Red Tide patches, concentrated by the converging columns and advecting seaward with them, are blown onshore along with the shallow wind drift. A persistent northwest wind will have similar effects on the Florida Keys and the lower portions of the west coast, while a transient northwest wind may merely advect the Red Tide patches directly from the converging current in the north to the southeastern branch of the eddy, to be carried ashore by the northbound diverging branch of the eddy. The Red Tide outbreak of November, 1952 [CHEW, 1953; MARINE LABORATORY, 1954] appears to have followed this pattern.

Another effect of a westerly wind is the generation of a superficial southbound current superposed on the counter-clockwise movement of the Florida west coast cyclonic eddy. A segment of the southbound current has been observed, [MARINE LABORATORY, 1954]. In this case the Red Tide movement may differ considerably from the depicted pattern.

The net effects of a strong offshore wind are more obscure. Against the immediate advantage of keeping possible Red Tide patches away from shore is pitted the longer term disadvantage of possibly having 'seeded' the offshore current with exceptionally large volumes of estuarine water, which, because of strong vertical turbulence may carry within them favorable incubating conditions for a Red Tide Bloom.

Discussion--The permanence of the essential features of deduced offshore circulation is suggested not only by the current charts mentioned and by cruise 3-2C in 1952, but also in part by three other works. The first is that of GRAHAM and Others [1954] who studied the phosphorus content of the waters along an east-west section from Boca Grande Pass west to the 100-fm depth for a period of 16 months in 1949-1950. Their 50-fm and 100-fm stations were located respectively in the SSE-ward estuarine tongue and the northern salient of the loop-current water north of Station 9 (Fig. 2). Using the integral mean concentration of the total phosphorus in the water column as an indicator of water mass they concluded tentatively that the water mass at the 50-fm station is different from that at the 100-fm; this fact is also clearly indicated by the present analysis. Incidentally, they also tried to trace the water movement by observed phosphorus values; in this they were handicapped by their station plan which confined the stations to a single line. Since north-south advection can bring about the phosphorus, temperature, and salinity changes observed by them, their conclusion with respect to possible upwelling must be abandoned.

The second work supporting the essential features of the deduced offshore circulation is that of SMITH and Others [1951], in which the distribution of surface convergence and divergence was computed from surface drift vectors given in the H. O. current charts cited. An area of horizontal convergence was generally found throughout the year over that portion of the continental shelf roughly corresponding to the confluence region of the Florida west coast estuarine waters west of Tampa; or in terms of the cyclonic eddy, the general area of convergence corresponds roughly to the northwestern half of the eddy. And encouragingly, the general area of divergence corresponds to the southeastern half of the eddy, confirming the conclusions set forth in this paper.

The third work supporting an essential feature of the deduced circulation is an unpublished study by Ilmo Hela, Frank Chew, and L. P. Wagner, who found a portion of the cyclonic eddy WSW of Tampa by means of the Geomagnetic Electrokinetograph in November, 1954.

The time spread of the cruise data analysed is 11 days from the first to the last station, but it is more nearly synoptic for Stations 8 to 17 (occupied in four days) which are of the greatest concern here. In any case, it has been shown that the essential features revealed by the present analysis were found in previous years by other workers in agreement with SVERDRUP and Others [1946, p. 641] who wrote: "In the Gulf of Mexico several large eddies exist, and all of these appear to be semipermanent features..." Thus a near-steady state may probably be assumed to hold and hence the indicated time spread to be reasonable.

The possible effects of astronomical tides have not been analysed but are here assumed negligible.

Attention has been given solely to the offshore area. Such problems as the biological and physical factors of Red Tide in the nearshore and offshore areas including the problem of how the offshore area may be seeded with Red Tide organisms which are apparently derived from shore areas, as existing studies seem to indicate are untouched.

Summary and conclusions--Whatever the initiating mechanism of the Red Tide outbreaks off the Florida west coast, the many available observations on the movements of discolored water and dead fish agree on the following:

(1) Fish mortality has been observed along the chain of Florida Keys northward along the Florida west coast to Clearwater. The mortality generally moves northward and shoreward. Recent observations by this Laboratory confirm these essential features with modifications.

(2) During periods of Red Tide mortality, it is generally believed that there is a large band of dead fish some tens of miles offshore. The horizontal dimensions of the band are several miles wide and 20 to 30 mi long. When there is a westerly wind the large band as a whole would be advected shoreward and, apparently, the most severe attacks are experienced during such wind regimes; for example, the Red Tide attack of August 8 to 12, 1954.

The present paper attempts to provide an advection pattern for (1), and a convergence mechanism for observation (2). For the former, Rossby's jet and the vorticity equation are employed. For the latter, the critical factors examined are the movements of the water column as a whole and the slope of the topographic bottom.

While further support is desirabel to desirable to demonstrate that the offshore water columns move as units, it is concluded that the suggested convergence mechanism is supported by existing data and provides for concentration of the right order of magnitude within a reasonable period of time, and that the deduced advection pattern includes a tendency for shoreward movement.

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WAVE TRANSFORMATION IN SHOALING WATER

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Abstract--A series of wave-recorders was installed from the surf zone to a point nearly a mile offshore, to study the transformation of waves in shoaling water. Examples of data taken by the recorders are presented, and the records are correlated with one another. The theory for waves traveling in shoaling water is given, and a table is presented for use in predicting the theoretical travel time for periodic waves on beaches of small constant slope. From the data obtained, it appears that under favorable circumstances wave records obtained in water as deep as 81 ft (below MLLW could be correlated with records obtained in the vicinity of the surf zone in 12 ft of water, the recorders being located nearly 4200 ft apart. Travel time is predicted quite well by theory.

Introduction--It has been observed that a person often can visually follow long-period waves as they move along a pier onto a beach. This is because they usually are in relatively shallow water, and consequently their transformation due to their dispersive qualities is rather small. When one tries to track them in deeper water, the problem becomes more complicated. In fact, the problem of merely trying to observe the forward movement of wave crests in relatively deep water is quite difficult, and one does not know whether he has lost track of a wave or whether the wave has disappeared owing to dispersion or because of the effect of the movement of crossed wave systems. Because of this, two more-reliable methods were utilized to study the problem of wave transformation. One was to take photographs of waves moving from offshore, along a pier, and onto a beach. The second method was to install wave-recorders at various locations offshore and to attempt to correlate the records.

Through the cooperation of the Santa Cruz Portland Cement Co., the University of California was given permission to use an abandoned cement loading pier at Davenport, California, for the field studies of wave transformation (Fig. 1). The pier extended 2200 ft seaward of the beach and was exposed to the large waves from the North Pacific area.

Travel time for periodic waves on beaches of small constant slope--The purpose of this section is to present a table from which graphs can be constructed permitting the rapid estimation of the time required for ocean waves to travel from some offshore position to the breaker zone. Applications of these graphs to ocean records are discussed in the following section. In addition to the immediate use for determining the travel time of individual waves, the functions computed here are involved in the prediction of a wave record near the shore from an offshore record.

In general the transformation of ocean waves in shoaling water is a complex process which is not as yet fully understood. A partial understanding of this process can be gained by representing the complex sea as a sum of sinusoidal waves of different amplitudes, periods, phases, and directions of motion. Clearly a resultant wave crest deforms as it moves, making it difficult to precisely define the term 'wave velocity.' However this term might be defined, it depends on the ratio of component amplitudes, wave periods, depth of water, and bottom slopes. The rate of deformation of a single elevation depends upon the variation of component wave speeds and the angular divergence of directions of propagation.

Clearly the travel time can be obtained for waves of permanent form from a knowledge of the refraction angle and of the wave velocity, which in turn depend in the simplest case on the water depth and wave period. A similar situation arises in the determination of water depth by wave velocity methods. In this case one knows, say, the wave velocity and period, and seeks to determine the depth from a formula. Several complicating aspects of these problems have been discussed by FUCHS [1953]. Thus it appears that large-amplitude crests generally deform at a slower rate than small-amplitude crests. The deformation is slower the smaller the depth, since the variation of wave speeds is smaller in shallower water for the same range of periods. For beaches of slope less than 1/10 the effect of slope on wave velocity is very small. Owing to selective refraction of the different period components of an irregular wave train which is long-crested in deep water, the

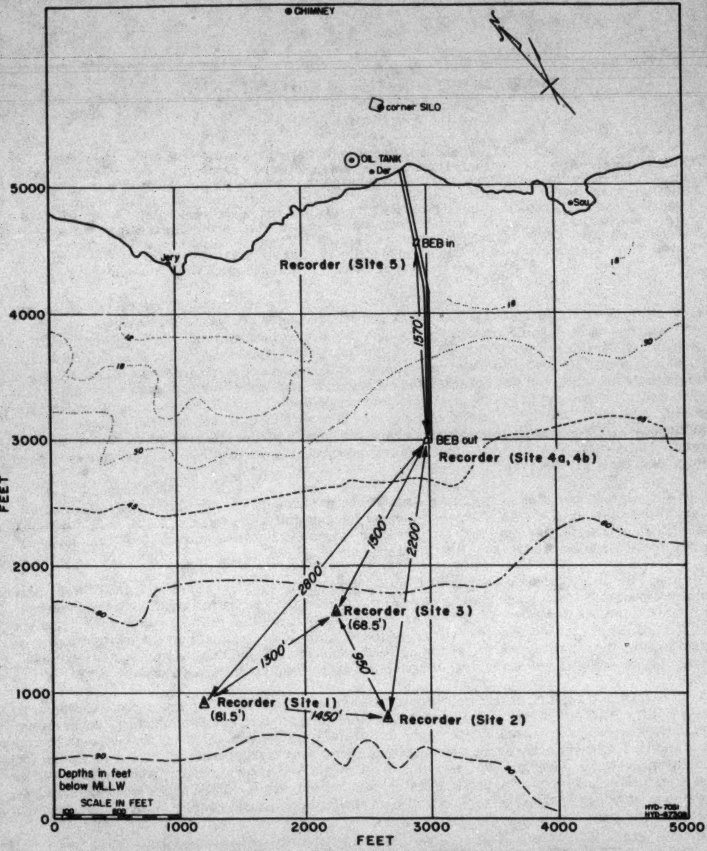

CHIMNEY
corner SILO
OIL TANK
Der
Sou
Jery
BEB in
Recorder (Site 5)
1570'
BEB out
Recorder (Site 4a, 4b)
2800'
1500'
2200'
Recorder (Site 3)
(68.5')
1300'
950'
Recorder (Site 1)
(81.5')
1450'
Recorder (Site 2)
18
30
45
60
90
Depths in feet below MLLW
SCALE IN FEET
FEET
0
1000
2000
3000
4000
5000
FEET
0
1000
2000
3000
4000
5000
HYD-7081
HYD-67308

Fig. 1--Location of wave recorders and survey stations, Davenport, California; depth contours from C and GS chart; seasonal changes or scouring had increased the depth at the end of the pier to 46 ft at the time the gages were installed

transformation in shoaling water can be quite complex. The effects are especially pronounced for small periods and large refraction angles. With these limitations in mind, we assume that the wave velocity of a crest depends upon the water depth immediately below the crest and on the wave period according to the familiar formula for sinusoidal waves in water of the same constant depth.

The following symbols have been used in the calculations:

α = local angle between a wave crest and the beach contour
β = beach slope (assumed constant)
c = wave velocity, ft/sec
h = water depth, ft
L = wave length, ft
T = wave period, sec
t = travel time (sec) from h_1 to h_2, with angles α_o, β, period T
x = horizontal distance (ft) measured perpendicular to the parallel beach contours with origin at the deep-water point for which $h/5.12\,T^2 = 0.5$

The subscript o refers to the deep-water point for which

$$L_o = gT^2/2\pi = 5.12\,T^2, \qquad h/L_o = 0.5$$

Evidently

$$t = \int_{x_1(h_1)}^{x_2(h_2)} \frac{dx}{c\cos\alpha} = \frac{T}{\beta}\int_{h_1/L_o}^{h_2/L_o} \frac{d(h/L_o)}{c/c_o\cos\alpha} = \frac{T}{\beta}\left[S_{\alpha_o}\left(\frac{h_1}{L_o}\right) - S_{\alpha_o}\left(\frac{h_2}{L_o}\right)\right] \quad \ldots\ldots\ldots (1)$$

where

$$S_{\alpha_o}\left(\frac{h}{L_o}\right) = \int_{h/L_o}^{1/2} \frac{d\,(h/L_o)}{c/c_o\cos\alpha} \quad \ldots\ldots\ldots\ldots\ldots (2)$$

Assume that the wave velocity is independent of beach slope, and is given by the formula for water of constant depth [FUCHS, 1953]. Assume, furthermore, that the refraction follows Snell's law $\sin\alpha/\sin\alpha_o = c/c_o$. The integrals can then be evaluated numerically by using existing tables [WIEGEL, 1954].

The function $S_{\alpha_o}(h/L_o)$ has been computed by finite difference methods for α_o = 70°, 50°, 30°, 15°, 0°, and the results presented in Table 1. The travel time t can easily be obtained by use of this table and the above formulas. FUCHS [1954] presents a series of graphs of TS_{α_o} versus h to facilitate rapid determination of t.

Similar calculations can be made using the group velocity c_g instead of the wave velocity c. The travel time, in such a case, would presumably be the time taken for a group of high waves to travel the given distance. The refraction of wave groups is so complex that we only present results for normal incidence, that is, $\alpha = 0°$. The function R_o, corresponding to S_o, but with c replaced by c_g, is also given in Table 1. The travel time is obtained, as before, by dividing the appropriate tabular difference by the beach slope and multiplying by the wave period.

For routine application, where α_o, h_1, h_2, β are given, it is convenient to derive a graph of t versus T. The form of this graph for both large and small periods is easily obtained. For sufficiently small periods, essentially deep-water conditions will prevail at both depths. Hence $c = (g/2\pi)\,T$, and

$$t \simeq \frac{2\pi\,(x_2 - x_1)}{g\cos\alpha} \cdot \frac{1}{T} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

for small T. On the other hand, for sufficiently large periods, essentially shallow-water conditions will prevail at both depths, hence $c = \sqrt{gh}$, and

$$t \simeq \frac{2}{\sqrt{g\beta}}\left(\sqrt{x_2} - \sqrt{x_1}\right) = t_m \quad \ldots\ldots\ldots\ldots\ldots (4)$$

for large T. Thus the graph of t versus T behaves like 1/T for small T and approcaches t_m asymptotically for large T.

Table 1--Table of S_{α_0} and R_{0_0}

h/L_0	S_{α_0}					R_{0_0}
	70°	50°	30°	15°	0°	
0.50	0.	0	0	0	0	0
0.45	0.142	0.078	0.058	0.052	0.050	0.098
0.40	0.280	0.155	0.116	0.104	0.101	0.194
0.35	0.413	0.232	0.174	0.157	0.152	0.288
0.30	0.539	0.309	0.233	0.210	0.203	0.379
0.25	0.655	0.386	0.293	0.264	0.256	0.468
0.20	0.762	0.463	0.355	0.321	0.311	0.553
0.19	0.782	0.478	0.367	0.332	0.322	0.570
0.18	0.802	0.494	0.380	0.344	0.333	0.587
0.17	0.822	0.509	0.393	0.356	0.345	0.604
0.16	0.841	0.525	0.406	0.368	0.357	0.610
0.15	0.860	0.540	0.419	0.381	0.369	0.637
0.14	0.879	0.556	0.433	0.393	0.381	0.654
0.13	0.898	0.572	0.447	0.406	0.394	0.670
0.12	0.917	0.588	0.461	0.420	0.407	0.687
0.11	0.936	0.604	0.475	0.433	0.420	0.704
0.10	0.955	0.621	0.490	0.447	0.434	0.722
0.09	0.974	0.638	0.505	0.462	0.449	0.739
0.08	0.993	0.655	0.521	0.477	0.464	0.757
0.07	1.013	0.674	0.538	0.493	0.480	0.776
0.06	1.033	0.692	0.556	0.510	0.496	0.795
0.05	1.054	0.712	0.576	0.528	0.514	0.815
0.04	1.077	0.734	0.595	0.548	0.534	0.837
0.03	1.101	0.757	0.618	0.571	0.556	0.861
0.02	1.129	0.785	0.644	0.597	0.582	0.889
0.01	1.164	0.819	0.678	0.631	0.616	0.924
0.009	1.168	0.823	0.682	0.634	0.620	0.928
0.008	1.173	0.828	0.687	0.639	0.624	0.933
0.007	1.177	0.832	0.691	0.644	0.629	0.937
0.006	1.183	0.837	0.696	0.649	0.634	0.943
0.005	1.188	0.843	0.702	0.654	0.640	0.948
0.004	1.194	0.849	0.708	0.660	0.646	0.954
0.003	1.201	0.856	0.715	0.667	0.652	0.961
0.002	1.209	0.864	0.723	0.675	0.660	0.969
0.001	. . .	. . .	. . .	. . .	0.671	. . .

Wave refraction--With the exception of the locally generated waves, most waves at Davenport came from the west through the northwest sector. This wave direction, combined with the local hydrography, caused the waves to refract to a considerable extent. Using available U. S. Coast and Geodetic Survey charts and work sheets as a basis, refraction drawings [JOHNSON, O'BRIEN, and ISAACS, 1948] were made for the most common wave periods and directions. The results obtained from these drawings are presented in Table 2. The Table shows the change in angle the waves make as they move from deep water past the five wave-recorder sites.

Wave-recorders--The general plan of the wave-recorder installation was to install several step-resistor type gages along the pier, and several pressure-head type wave-recorders seaward of the end of the pier. This made it possible to obtain records simultaneously from all the wave meters to determine whether the records from the wave meter farthest at sea could be correlated with the records from each meter closer to shore, as the waves progressed toward the shore.

The majority of the longer-period waves at Davenport came from WNW to NW and refracted to a considerable extent before breaking on the small pocket beach at the base of the pier. The refraction can be seen in the set of typical refraction drawings in Figure 2. The waves were observed

Table 2--Refraction data, Davenport, California

T	Direction	Item	Changes between instruments				
			Deep water to site 1	Site 1 to site 4	Site 1 to site 5	Site 2 to site 4	Site 3 to site 4
sec							
		Refraction coef.	. . .	0.90	0.78	0.92	0.93
10	WNW	Travel dist. ft	. . .	2800	4000	1800	1500
		Angle change	20°30′	12°30′	51°	5°15′	6°
		Refraction coef.	. . .	0.95	0.87	0.95	0.95
12	WNW	Travel dist. ft	. . .	2800	4100	1680	1590
		Angle change	29°	10°30′	42°30′	18°	16°30′
		Refraction coef.	. . .	0.87	0.79	0.92	0.91
14	WNW	Travel dist. ft	. . .	2800	4150	2350	1500
		Angle change	31°	16°	39°	16°	12°
		Refraction coef.	. . .	0.85	0.81	0.94	0.96
16	WNW	Travel dist. ft	. . .	2700	4200	2150	1600
		Angle change	37°	14°	42°	14°30′	11°
		Refraction coef.	. . .	0.93	0.84	0.96	0.97
14	W	Travel dist. ft	. . .	2630	4100	2150	1500
		Angle change	19°30′	9°	29°30′	9°30′	7°
		Refraction coef.	. . .	0.93	0.76	0.92	0.94
14	W	Travel dist. ft	. . .	2700	4200	1950	1600
		Angle change	53°	16°30′	41°30′	18°	13°30′

for a long interval of time to determine this most usual direction. A curved line was run from the end of the pier in such a manner that it followed a typical orthogonal. Two pressure heads were placed along this line (1 and 3, Fig. 1). A third pressure head was placed on a line roughly directly seaward of the pier end at site 2 in 85.5 ft of water. Two types of pressure heads were used. These were the University of California Mark III [CHINN, 1949] and the Mark IX [SNODGRASS, 1954]. The Mark III heads were used as they were available before the necessary Mark IX heads could be manufactured, although they did not have nearly as long a sea life as the Mark IX.

Beach Erosion Board step-resistor gages (parallel type) [CALDWELL, 1948] were used alongside the pier. It was first thought that it would be necessary to install three gages; however, it was found that one at the end of the pier and one in the vicinity of the breakers (for medium-sized breakers) would be sufficient. In addition to these surface recording gages, a subsurface pressure-type meter was installed 1.5 ft above the bottom (44.5 ft below MLLW) directly under the pier-end Beach Erosion Board gage, during part of the tests so that correlation could be obtained directly between two pressure recorders rather than between a pressure recorder and a surface measuring gage.

Wave records-- Many charts from the wave-recorders were examined to determine whether it would be possible to see visually the correlations among the surface-time histories obtained by the various recorders. It appeared relatively easy to do so for the two recorders in the most shallow water; that is, the Beach Erosion Board gage at the pier end and the Beach Erosion Board gage in the vicinity of the breakers. A typical pair of records is shown in Figure 3.

In order for the two sets of records to be compared, it was necessary to translate one in time by 52 sec. This was checked using Table 1 for waves of an average period of 13.5 sec, traveling from water 51 ft into water 17.5 ft (tide stage + 5 feet) deep over a 1/47 slope for a deep-water wave angle of 70°. The wave-phase travel time was found to be 55 sec. For a deep-water wave angle of 50°, the wave-phase travel time was found to be 56 sec. The actual wave direction was within these limits. This also compares very well with the results of the linear least-squares method of PUTZ [1955], who found that for an average period of 15 sec the time lag which gave the best correlation was 50 sec.

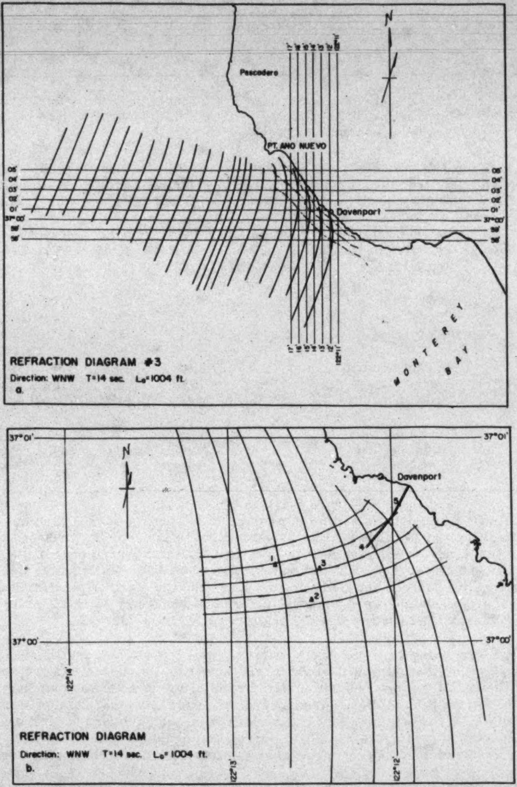
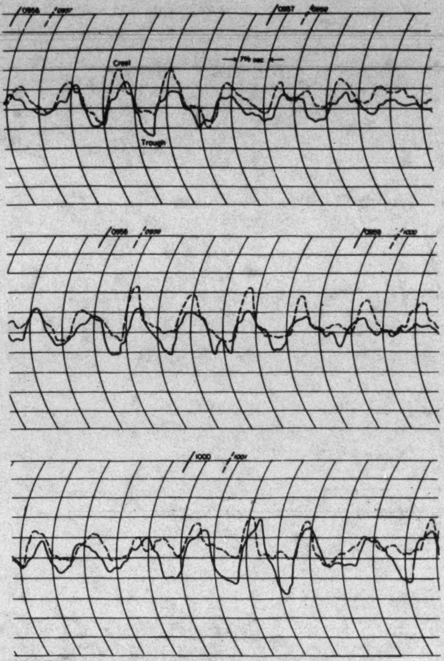

N
Pescadero
PT. ANO NUEVO
Davenport
05'
04'
03'
02'
01'
37°00'
59'
58'
MONTEREY BAY
REFRACTION DIAGRAM #3
Direction: WNW T=14 sec. L₀=1004 ft.
a.
37°01'
37°00'
N
Davenport
1
2
3
4
5
122°14'
122°13'
122°12'
REFRACTION DIAGRAM
Direction: WNW T=14 sec. L₀=1004 ft.
b.

Fig. 2--Typical refraction drawing (a) from deep water to the vicinity of the pier at Davenport; (b) showing details in the vicinity of Davenport; note locations of wave-recorders

When the waves were very large, or when they were of medium height and the tide was low, the waves would break before reaching the inshore recorder, and the recorder would be measuring a mass of tumbling air and water. At other times, strong local winds would blow, generating waves often nearly at right angles to the swell. Under these conditions it was very difficult, if not impossible, to correlate the records visually.

The problem of visually correlating the records obtained by the pressure head in 81.5 ft of water, 2800 ft seaward of the pier end with the record from one of the recorders along the pier was more difficult, because of dispersion, short-crestedness, and often the presence of more than one



5 Feb 1954

--- Catwalk BEB gage (location 5) —— Pier end BEB gage (location 4b)

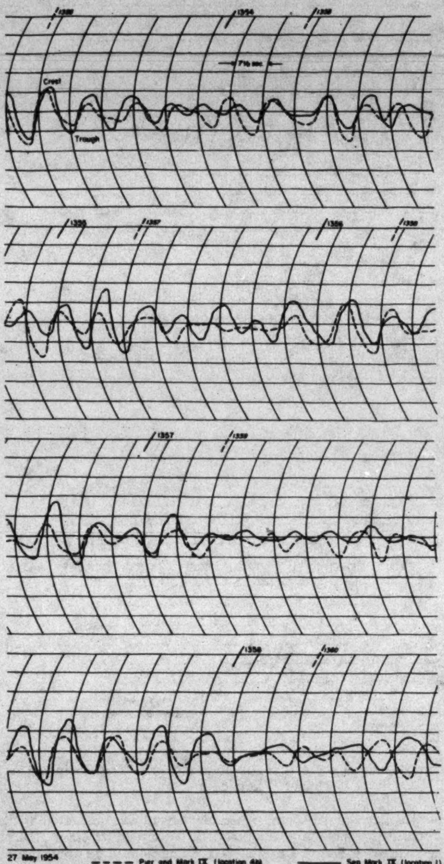
Note: The vertical scales of the two records are not the same, nor are the locations of their zero axes. Time lag is 52 seconds.

Fig. 3--Comparison of wave records obtained 1570 ft apart in water 51 and 17.5 ft deep

wave system. In order to simplify the problem, a pressure head was installed at the end of the pier so that the records from two pressure heads could be examined together, the pier-end pressure head and the surface-recording Beach Erosion Board gage could be correlated, and finally the records from the two Beach Erosion Board gages correlated.

In Figure 4 is presented a sample of the visual correlation between the two pressure-recorders, one in 83.5 ft and the other in 48 ft of water (tide stage +2 ft), 2800 ft apart. The average period of the higher waves was ten seconds, the slope between the two stations was 1/79, and the time lag was found to be 101.5 sec. For a deep-water wave angle of 90°, an extrapolated travel time of 100 sec is predicted by use of Table 1. A study of the weather maps for this date showed the waves to be from NNW, which would make an angle of about 90° with the coast in this area.

The most difficult pair of wave-recorders to obtain visual correlation between consisted of the pressure head in 81.5 ft and the Beach Erosion Board gage located in the vicinity of the breaker zone

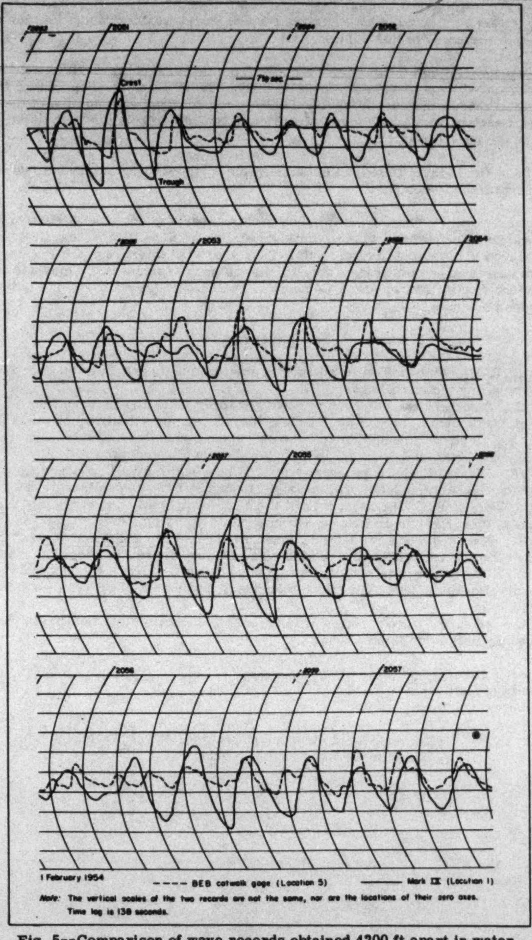


27 May 1954 – – – – Pier and Mark IX (location 4B) ———— Sea Mark IX (location 1)

Note: The vertical scales of the two records are not the same, nor are the locations of their zero axes. Time lag is 101½ seconds.

Fig. 4--Comparison of wave records obtained 2800 ft apart in water 83.5 and 48 ft deep

(12.5 ft below MLLW). Not only was the travel distance greatest, but the orthogonals of waves were such that the part of the wave moving over the offshore pressure head may or may not be the part moving past the inshore gage. In Figure 5 is presented an example of the records. The travel time as computed from the lag necessary to obtain best visual correlation between the two records was 138 sec. Using the average wave period of 13 sec, and a composite slope of 1/64 for a tide stage of +4 ft, use of Table 1 leads by extrapolation to a prediction of 123 sec for an almost - 90° deep-water wave angle. A study of the weather maps for this date showed the waves to be from NNW, which would again make an angle of about 90° with the coast in this area.



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Note: The vertical scales of the two records are not the same, nor are the locations of their zero axes. Time lag is 138 seconds.

Fig. 5--Comparison of wave records obtained 4200 ft apart in water 85.5 and 16.5 ft deep

Photographic coverage--Advantage was taken of the tall cement storage silos located on the cliff above the pier. Both motion pictures (16 mm) and photographs taken with a 20-inch F 56 Fairchild aerial camera were obtained simultaneously from the same location, while the wave-recorders were in operation. The waves could be identified in the vicinity of the pier, but it was nearly impossible to do so in the vicinity of the wave-recorders farther offshore. Under ideal conditions, large swell with a very light wind to give surface texture, clear weather, and a low Sun angle, it might be possible to make use of this system.

Conclusions--An inspection of the records from the wave-recorders located offshore at Davenport, California, showed that waves could be tracked from water as deep as 81.5 ft (below MLLW) to the breaker zone, a distance of nearly 4200 ft, from a visual examination of the records, provided there were not local wind waves of sufficient magnitude relative to the swell to mask the swell on the offshore recorder.

The theoretical travel times, as given in Table 1, appear to give predictions of sufficient accuracy from a practical standpoint.

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ON WIND-GENERATED WAVE MOTION AT SUBSURFACE LEVELS

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Abstract--The characteristics of ocean waves at subsurface levels are derived on the basis of wave spectra as a function of depth. It is shown that the decrease of total wave energy in the composite wave motion with depth is much less than would be expected for a 'significant' wave of the same energy at the sea surface. The wave properties change considerably with increasing depth as a result of the different attenuation of the individual wave components in the spectra. A dimensionless parameter which contains both of the variables, wind velocity and depth, simplifies the graphical representation of the derived relationships and their practical application for determining the properties of subsurface wave motion.

Introduction--One aim of ocean-wave research is to obtain adequate information about the characteristic properties of the wave motion at the sea surface and at different levels below the surface, and to relate these properties to the wind velocity, fetch, and duration of wind action. This information can be obtained either directly from observations; that is, from wave records taken at the surface and at subsurface levels; or it can be derived theoretically if the energy spectrum of the composite wave motion is known.

The spectral representation of wind-generated ocean waves as proposed recently [NEUMANN, 1953] seems to yield properties which represent actual waves in the most realistic and consistent way yet achieved theoretically. When combined with the theory of a quasi-stationary Gaussian process, it has been possible to derive the observable sea surface characteristics of wind-generated sea, and to explain many of the complicated properties of the waves in the generating area as well as in the area of decay [PIERSON, 1954; NEUMANN, 1954]. Since the wave spectrum describes uniquely not only the free-surface motion but also the wave motion at subsurface levels, it offers a way to relate the subsurface wave characteristics to the sea surface characteristics and to the wind velocity quantitatively.

At present, very little empirical information is available on the wave characteristics at subsurface levels. Most of the wave records used in the past for ocean-wave analysis were obtained by measuring the pressure fluctuations produced by the waves at selected depths at or near the bottom. Such data may provide the necessary observations for relating the wave characteristics at subsurface levels to the characteristics of the wave motion at the free surface and to the wind, if there were no serious disturbances from shallow water and bottom effects. The modification of the deep-water wave motion by shallow water effects is subject to many local conditions which may change from place to place. Pressure type records taken at the bottom and near the shore are less representative for establishing uniform relationships between the wind and sea state characteristics.

In the following, the wave spectrum will be used for a theoretical derivation of the wave characteristics at subsurface levels beyond the influence of the bottom and to establish their relationship to the wind velocity. As in the case of the wave characteristics at the sea surface, fixed relationships between the statistical properties of the subsurface wave motion and the wind can be given only for a fully arisen sea. In the case of a non-fully developed sea, a great number of different fetch and duration combinations are possible. Such cases have to be dealt with individually, according to methods suggested previously [NEUMANN, 1953].

The energy spectrum at subsurface levels--Let $(H_T)_o^2$ be the square of the wave height of an individual wave component in an infinitesimal spectral band $T \pm \delta T$ at a given wind velocity v, and at the surface. At the depth z, the maximum vertical displacement of a water particle from its undisturbed position for this individual wave component equals $0.5\,(H_T)_z$, and the spectral 'wave height' at the depth z is given by

$$(H_T)_z^2 = (\delta h_T^2/\delta T)_z = (H_T)_o^2\, e^{-(4\pi z/\lambda)} \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

where h_T^2 denotes the square of the 'height' of individual waves in the continuous spectrum, and λ the spectral wave length. The term $\delta T \rightarrow 0$, also $\delta h_T^2 \rightarrow 0$, but $(H_T)_z^2$ approaches a finite value.

If $\delta U_T/dT$ represents the spectral energy density in an infinitely small period band dT, then, at the depth z

$$(\delta U_T)_z = (1/8)\, g\rho\, (H_T)_o^2\, e^{-(4\pi z/\lambda)}\, dT \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

g is the acceleration of gravity and ρ the density of the water.

By making use of a result derived in a previous paper [NEUMANN, 1953], where the square of the surface wave heights in any given spectral band may be represented by

$$(H_T)_o^2 = C(g^2T^4/4\pi^2) \exp\left[-2(gT/2\pi v)^2\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

and by substituting the relationship

$$4\pi/\lambda = 8\pi^2/gT^2$$

it follows for the depth z that

$$(\delta U_T)_z = KT^4 \exp -\left[g^2T^2/2\pi^2v^2 + 8\pi^2z/gT^2\right]dT \quad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

where

$$K = Cg^3\rho/32\pi^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

and the constant C has the value 8.27×10^{-4}/sec.

Eq. (4) represents the energy spectrum of a fully arisen sea at the depth z in terms of periods. By expressing (4) in terms of frequencies, $\nu = 2\pi/T$, the spectrum at the depth z can be written

$$(\delta U_\nu)_z = K^* \nu^{-6} \exp\left[-2(g^2/\nu^2v^2 + \nu^2z/g)\right]d\nu \quad \ldots\ldots\ldots\ldots\ldots \quad (6)$$

where

$$K^* = -Cg^3\rho\pi^3$$

As an example, Figure 1 shows the distribution of wave energy in the spectrum at the surface, z = 0, and at different depths at a wind velocity of v = 15.43 m/sec (30 knots). Some characteristic properties of the wave motion at subsurface levels can immediately be recognized. With increasing depth, the wave energy attenuates rapidly at the low-period end, especially in the upper layer beneath the surface, and the optimum band, where most of the spectral energy is concentrated, shifts toward lower frequencies as the spectrum narrows.

Such a shift of the optimum band was found to be indicated in the few cases of wave pressure records analyzed by PIERSON and MARKS [1952] and PIERSON [1954], yet it is not possible at present to check the quantitative results which follow from the theoretical spectrum by observations. Nevertheless it is seen, that for computing the properties of the free-surface disturbances from data available in a given pressure record at the depth z, the spectrum must be amplified considerably more for high frequencies than for low frequencies. As pointed out by PIERSON and MARKS [1952] the neglect of this effect explains many of the seeming discrepancies reported in the literature on the relationship between pressure records and actual free surface records.

The energy spectrum (6) permits the derivation of quantitative relationships between subsurface wave characteristics and the corresponding sea surface characteristics for fully arisen seas at different wind velocities.

Maximum of spectral energy and total wave energy at subsurface levels--The period of the energy maximum, $(T_{max})_z$, in the wave spectrum is a significant property of the composite wave motion. Outside the generating area, and at the sea surface, it represents the average 'period' of the highest swell to pass. (Here and in the following, the word 'period,' in single quotation marks, means the time interval between successive crests of the apparent waves, as contrasted with the true period of an individual wave component.) $(T_{max})_z$ is derived from the spectrum by differentiating

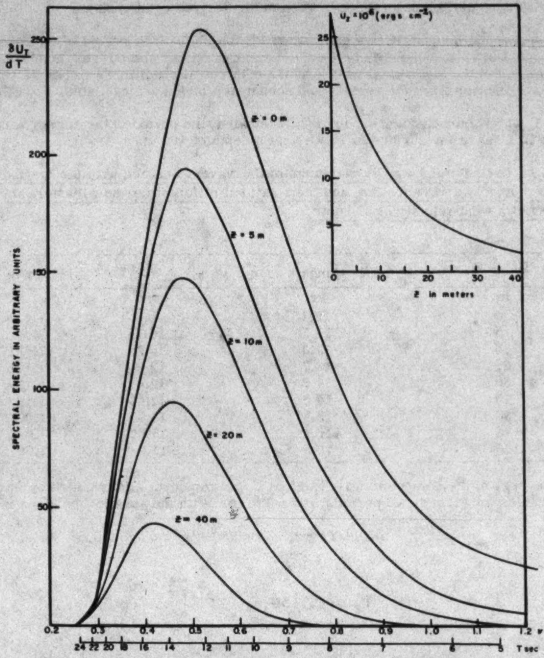

Fig. 1--Energy spectra of fully arisen sea for v = 30 knots, at the surface (z = 0 m) and at 5, 10, 20, and 40 meters of depth; the inset shows the total wave energy for v = 30 knots as a function of the depth z

(6) with respect to ν and setting the result equal to zero. It follows that the frequency of the energy maximum at different depths is given by

$$(\nu_{max})_z^2 = (4g^2/3v^2)[1 + \sqrt{1 + (16gz/9v^2)}]^{-1} \quad \ldots\ldots\ldots\ldots\ldots \quad (7)$$

or

$$(T_{max})_z = (T_{max})_o \sqrt{0.5 + 0.5\sqrt{1 + 16\xi/9}} \quad \ldots\ldots\ldots\ldots\ldots \quad (8)$$

where

$$(T_{max})_o = 2\pi\sqrt{3/2}\,(v/g) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

is the period of the energy maximum at the free surface (z = 0) [NEUMANN, 1954].

$$\xi = gz/v^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

is a dimensionless quantity which has been introduced for abbreviation. It will appear in all of the following relationships between the wave characteristics at subsurface levels and the wind velocity, and it simplifies considerably the representation of the derived relationships.

Eq. (8) represents the quantitative expression for the shift of the period of the energy maximum as a function of z and v. It can easily be found from observations and offers a good opportunity to check this property of the theoretical wave spectra with actual conditions as soon as reliable spectral analyses of wave records from the surface and subsurface levels are available.

In Table 1, which extends Figure 1 for a 30-knot wind, the period of the energy maximum increases from 12.1 sec at the surface to 16.9 sec at a depth of 100 m.

Table 1--Period of the energy maximum of the wave spectrum, average 'period' of the composite wave motion, and their ratio at different depths with fully arisen sea at a wind velocity of 30 knots

Depth Z	$(T_{max})_z$	$\bar{\bar{T}}_z$	$(T_{max})_z/\bar{\bar{T}}_z$
m	sec	sec	
0	12.1	8.6	1.41
5	12.55	10.15	1.24
10	13.0	10.9	1.19
20	13.7	12.0	1.14
30	14.3	12.8	1.12
40	14.8	13.45	1.10
50	15.2	13.95	1.09
75	16.1	15.05	1.07
100	16.9	15.9	1.06

The total energy of the composite wave motion, U_z, at the depth z is obtained by integrating (6) over all frequencies, or (4) over all periods, from 0 to ∞. With the substitution $T = y^{0.5}$ and

$$p = g^2/2\pi^2 v^2, \quad a/4 = 8\pi^2 z/g \quad \ldots\ldots\ldots\ldots \quad (11)$$

it follows that

$$U_z = \int_0^{\infty} (\delta U_T)_z = KP \quad \ldots\ldots\ldots\ldots \quad (12)$$

where

$$P = 0.5 \int_0^{\infty} y^{3/2} \exp[-(py + a/4y)]dy \quad \ldots\ldots\ldots\ldots \quad (12a)$$

The evaluation of the integral (12a) yields

$$P = (3/8)\pi^{0.5} p^{-2}(p^{-0.5} + a^{0.5} + (a/3)p^{0.5}) \exp(-ap)^{0.5} \quad \ldots\ldots\ldots\ldots \quad (13)$$

and with (5), (10), (11), and (13) it follows from (12) that

$$U_z = 3.125 \times 10^{-9} v^5 [1 + 4\sqrt{\xi} + (16/3)\xi] e^{-4\sqrt{\xi}} \quad [\mathrm{erg\ cm^{-2}}] \quad \ldots\ldots\ldots\ldots \quad (14)$$

where $g = 981\ \mathrm{cm/sec^2}$ and $\rho = 1$.

As was shown by NEUMANN [1953], $U_o = 3.125 \times 10^{-9} v^5$ is the total wave energy in a fully arisen sea at a wind velocity v (cm/sec). If a quantity $E = 2U_o/g\rho$ is defined, the wave height characteristics can be easily computed from the value E [PIERSON, NEUMANN, and JAMES, in press]. In a similar way the characteristics of the vertical water displacement at any level z can be derived by means of (14).

Example--Consider a fully arisen sea at a wind velocity v = 30 knots (15.43 m/sec), and the wave motion at a depth of 20 m. With $\xi = 0.824$ (see Eq. (10)), it follows from (14) that $U_z = 6.65 \times 10^6\ \mathrm{erg\ cm^{-2}}$, and $E = 13.3 \times 10^3\ \mathrm{cm^2}$. If the statistical methods used for computing the distribution of sea surface heights are adopted for the vertical water displacements at a given depth, a complete description of the characteristics of the vertical oscillations at subsurface levels can be given. For example, the average vertical water displacement $\bar{H}_z$, and the mean displacement of the 1/10 highest vertical oscillations, is, according to LONGUET-HIGGINS [1952],

$$\bar{H}_z = 1.772\ \sqrt{E} = 204\ \text{cm}$$

$$H_{1/10} = 3.600\ \sqrt{E} = 414\ \text{cm}$$

It follows that the average vertical displacement (twice the 'amplitude') of a small floating body at the depth of 20 m in fully arisen sea at v = 30 knots would be 2.04 m, and a fair approximation of the maximum vertical displacement at this depth would be given by the value $H_{1/10} = 4.14$ m. The corresponding vertical water displacements at the surface (average height $\bar{H}$, and height of the 1/10 highest waves) are in this case 4.1 and 8.4 m, respectively.

The decrease of total wave energy with depth is best expressed by the ratio

$$U_z/U_0 = [1 + 4\sqrt{\xi} + (16/3)\xi]e^{-4\sqrt{\xi}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

This ratio is plotted for practical use in Figure 2, and may be used for any combinations of wind speed and depth in the case of fully arisen sea. There is a great difference in the decrease of the total wave energy with depth between the composite wave motion of a fully arisen sea according to (15) and a simple harmonic 'significant' wave of equivalent total energy at the surface. According to the classical theory of waves, the energy of an individual 'significant' wave should decrease with depth like

$$(U_z/U_0)_{sign} = e^{-4\pi z/\lambda} = e^{-8\pi^2 z/gT^2} \quad \ldots . \quad (16)$$

where λ and T represent the fictitious 'significant' wave length and period, respectively. This wave length or period is usually considered to be constant with depth, which certainly is not the case. Note that (15) is only a function of z and v, whereas (16) depends on z and a fixed period T.

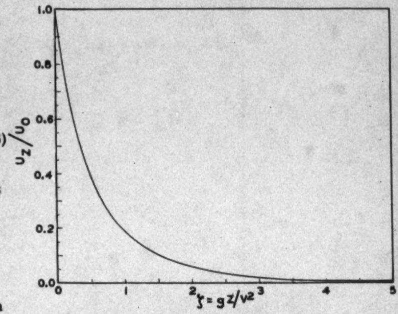

Fig. 2--Ratio U_z/U as a function of the dimensionless quantity $\xi = gz/v^2$

These results show again that any reduction of wave characteristics obtained by pressure records to free-surface wave characteristics must lead to incorrect results if such a reduction is based on some kind of significant wave. SNODGRASS [1951] found from observations that the actual wave heights were six to 25 pct greater than those computed theoretically from pressure records, and it is seen by a comparison of (15) with (16) that this error may be even greater if the depth where the pressure record is taken is increased.

An example is given in Figure 3 for a wind velocity of 30 knots. The dashed lines represent the ratio U_z/U_0 as a function of z with different assumptions as to the significant wave period (16), and the full-drawn curve shows the decrease of total wave energy for the actual wave motion, that is the ratio U_z/U_0 according to (15).

The significant 'period' does not have a simple interpretation in terms of the energy spectrum method of approach. It is usually defined to be the average value of the time intervals between the crests of the 1/3 highest waves. Thus, it is given as the 'period' of a fictitious wave which must be determined for each level separately. As a necessary consequence of the change of the wave spectra with depth (Fig. 1) such a 'period' must increase with depth.

The average wave 'period' as a function of depth--The average wave 'period' at the sea surface, $\bar{T}_0$, is defined as the average of time intervals between successive crests of the dominant apparent waves. It is a characteristic property of ocean waves which can be derived from the spectral representation. It can also easily be verified from wave records and by stop watch measurements, and it offers another convenient opportunity to check the reliability of the proposed spectrum [NEUMANN, 1954].

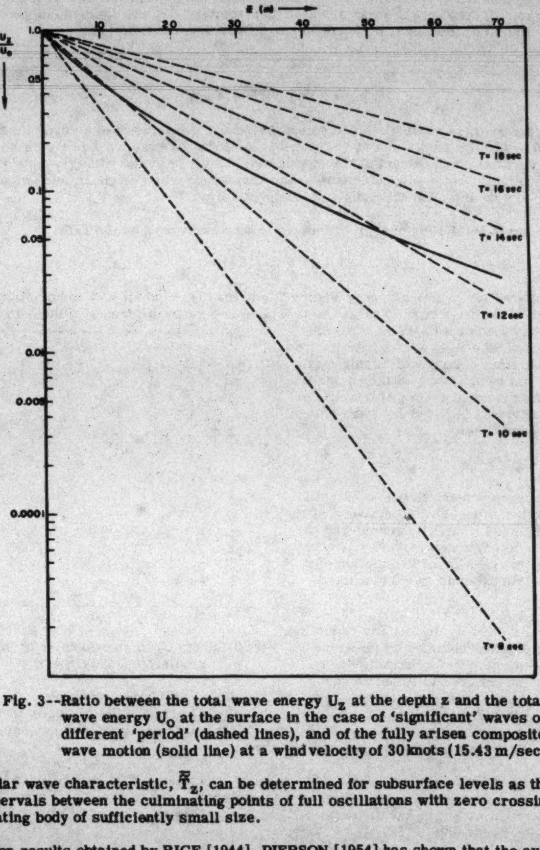

Fig. 3--Ratio between the total wave energy U_z at the depth z and the total wave energy U_O at the surface in the case of 'significant' waves of different 'period' (dashed lines), and of the fully arisen composite wave motion (solid line) at a wind velocity of 30 knots (15.43 m/sec)

A similar wave characteristic, $\overset{=}{T}_z$, can be determined for subsurface levels as the average of the time intervals between the culminating points of full oscillations with zero crossings of a submerged floating body of sufficiently small size.

Based on results obtained by RICE [1944], PIERSON [1954] has shown that the average time interval between the successive full oscillations in any given wave record can be calculated if the spectrum of the record is known. Applied to the energy spectrum used in this paper (6), the average 'period' of the wave motion at any level is obtained from

$$\overset{=}{T}_z = 2\pi\left[\int_0^\infty (\delta U_\nu)_z \Big/ \int_0^\infty (\nu^2 \delta U_\nu)_z\right]^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (17)$$

The integral in the numerator has been calculated in (12) with consideration of (13). The integral in the denominator yields

$$\int_0^\infty (\nu^2 \delta U_\nu)_z = -K^* 0.25\pi^{0.5} p^{-1.5} (1 + a^{0.5} p^{0.5}) \exp(-ap)^{0.5} \quad \ldots\ldots\ldots\ldots \quad (18)$$

where a and p have the same meaning as in (11).

With (12), (13), and (18), the average 'period' as a function of wind velocity and depth is obtained from (17), and

$$\overline{\overline{T}}_z = 2\pi\sqrt{(3/2p)}\left\{1 + (1/3)(ap)/[1 + (ap)^{1/2}]\right\}^{1/2} \quad \ldots\ldots\ldots\ldots\ldots \quad (19)$$

Since

$$2\pi\sqrt{3/2\,p} = \overline{\overline{T}}_o$$

is the average 'period' of the composite wave pattern at the surface [NEUMANN, 1953], it is deduced that at the depth z

$$\overline{\overline{T}}_z/\overline{\overline{T}}_o = [1 + (16\,\xi/3)/(1 + 4\sqrt{\xi})]^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (20)$$

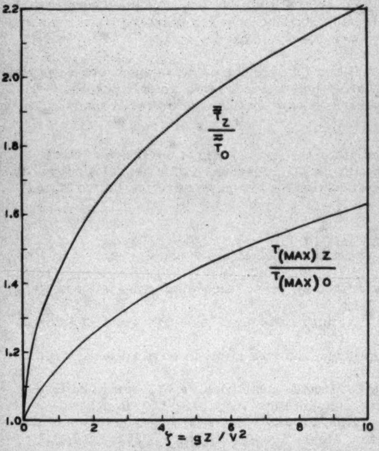

Fig. 4--Increase of the average 'period,' $\overline{\overline{T}}_z$, and the period of the energy maximum in the wave spectrum $(T_{max})_z$ with depth at different wind velocities, expressed by their ratio to the value at the sea surface

The increase of the average 'period,' $\overline{\overline{T}}_z$, with depth and wind velocity, and the corresponding increase of the period of the energy maximum, $(T_{max})_z$, is shown in Figure 4. Both characteristic properties of the composite wave motion are expressed by their ratio to the value at the sea surface, according to (20) and (8) as a function of the dimensionless parameter $\xi = gz/v^2$. The graphs cover all possible combinations of depth z and wind velocity v, and provide the necessary information about $(T_{max})_z$ and $\overline{\overline{T}}_z$ for practical applications (for example, 'wave' forecasting for subsurface levels).

The ratio between the period of the energy maximum in the wave spectrum and the average 'period' of the composite wave motion is constant at the sea surface, $(T_{max})_o/\overline{\overline{T}}_o = \sqrt{2}$, and thus it is independent of the wind velocity. At subsurface levels both these quantities and their ratio not only depend on z but also on v in a rather complicated way as the result of the change of the mathematical form of the wave spectra with depth. From (8) and (20) it is seen that with increasing depth at a given wind velocity, the ratio $(T_{max})_z/\overline{\overline{T}}_z$ decreases from the value $\sqrt{2}$ at the surface rapidly with the depth in the upper layers. However, this ratio does not approach the value one at very great depths, as might first be expected. With $\xi \to \infty$, it follows from (8) and (20) that

$$\frac{(T_{max})_{z\to\infty}}{\overline{\overline{T}}_{z\to\infty}} \to \frac{(T_{max})_o}{\overline{\overline{T}}_o}\sqrt{\frac{\sqrt{12}}{6}} = \sqrt{2} \times 0.76 = 1.055$$

Although the spectrum narrows considerably with increasing depth, it is found that a remarkable property of the wind-generated wave spectrum is that the ratio between the period of the peak of the spectrum and the average 'period' is always greater than one at any level between the surface and the depth where the wave motion practically vanishes.

For a fully arisen sea at a wind velocity of 30 knots the corresponding values were given in Table 1.

For some purposes, it is of interest to know the depth where the wave motion practically disappears. Let this depth be defined as the level where the total wave energy has decreased to five per cent of its value at the sea surface. From (15), or by means of Figure 2, this 'lower level' of the wave motion can be computed for fully arisen sea at different wind velocities. The result is

Table 2--Depth where the wave motion of fully arisen sea at different velocities practically disappears ($U_z = 0.05\ U_0$)

Wind velocity	Depth of $U_z = 0.05\ U_0$
m/sec	m
2	0.92
5	5.7
10	22.9
15	52
20	92
25	143

given in Table 2. This depth increases proportional to the square of the wind velocity. At the depth where $U_z = 0.05\ U_0$, the 'height' characteristics of the vertical displacements of water particles have decreased to approximately 22 pct of the surface wave-height characteristics.

Summary and conclusions--This paper has presented some information about the characteristics of wind-generated wave motion at subsurface levels. All the derived relationships are theoretical results which follow from the spectral representation of ocean waves. An urgent need today is to obtain series of wave records under many different sea state conditions and reliable spectral analyses to compare the theoretical results obtained from the proposed wave spectrum with observations.

The present paper does not exhaust the possibilities for applying the wave spectrum to special problems related to the wave motion at the surface and subsurface levels. Its only purpose is to discuss the most important characteristics of subsurface wave motion, and its relationship to the waves at the sea surface and the wind velocity.

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FACET SEPARATION DISTRIBUTIONS OF WIND-CREATED WATER WAVES

Allen Schooley

Abstract--Optical measurements made using a small water-wind tunnel, having a maximum fetch of 26 inches, indicate that the median minimum distance between the centers of facets of the surface is approximately 0.14 inch for wind velocities between 11 and 22 knots. In this range the first quartile of the distributions is about 0.09 inch and the third quartile is about 0.25 inch. Below 11 knots the median separation between the facets increases rapidly.

Flash pictures taken of a wind-disturbed water surface, with the axis of the camera perpendicular to the average plane of the surface and with the flash bulb substantially at the camera lens position, yield data regarding the distribution of facet slopes [SCHOOLEY, 1954]. Similar pictures of the wind-disturbed surface of a small water-wind tunnel, having a maximum fetch of 26 inches, have been used to optically determine the distributions of surface curvatures [SCHOOLEY, 1955]. It is the purpose of this paper to present the results of an analysis of data taken in connection with the previously reported curvature measurements. This analysis was made to yield information regarding the distributions of the distances between the facets.

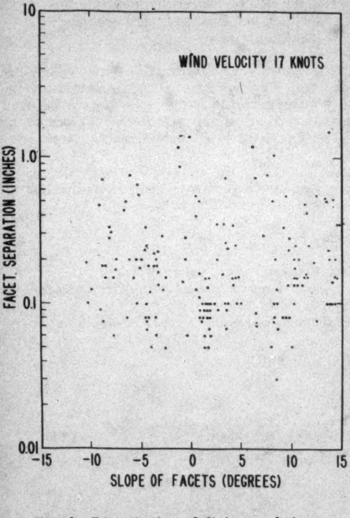

Fig. 1--Distribution of distances between facets for various facet slopes

Figure 4 of SCHOOLEY [1955] shows a typical flash picture of the water surface of the water-wind tunnel revealing the location of the facets with an 11-knot wind. Full-scale enlargements of 19 such pictures were made for various wind velocities. The shortest distance between centers from each facet to its neighbors was measured along three 1/4-inch wide strips drawn parallel to the center of the channel and separated from each other by 1/2 inch. Figure 1 gives the results of such measurements for one picture taken with a 17-knot wind. The logarithmic ordinate shows the facet separations in inches and the abscissa gives the slope of the facets in degrees.

For the purpose of this paper the facet separations for all slopes at a given wind velocity were lumped together and histograms made, Figure 2 being an example. In all cases, for wind velocities appreciably above the threshold, the histograms were skewed toward the lesser facet separations. (The wind-velocity threshold and method of wind measurement are given in SCHOOLEY [1955]). This skewness may mean that camera resolution is limiting the accuracy of the analysis of the data.

Since the data were appreciably skewed, further analysis was based on finding the median and first and third quartile values of the distributions [KENNEY, 1947]. Figure 3 shows the results of this work. The median value of facet separation is large for wind velocities just above the threshold of wave formation and drops rapidly to a quite constant value of 0.14 inch between 11 and 22 knots.

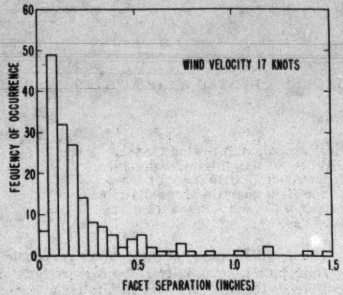

Fig. 2--Frequency distribution of facet separation

The shapes of the first and third quartile lines are similar. Between 11 and 22 knots the first quartile value of the facet separation distribution is about 0.09 inch and the third quartile value is about 0.25 inch.

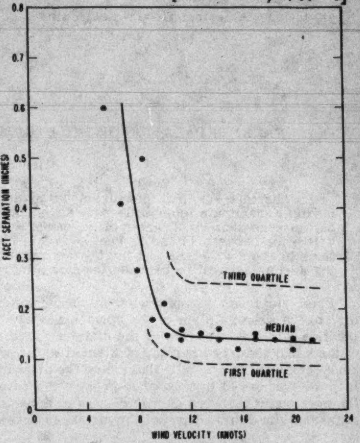

Fig. 3--Relation wind of velocity to the median, and first and third quartile facet separation

From Figure 1 it is evident that data were taken only between the limits of -10° to +15°. This was due to limitations of the experimental techniques used. Perhaps more accurate data would be obtained if these limits were extended since there may be an increase in the mean separation near the edges of the slope distributions. It is believed that this effect, if appreciable, would tend to make the transition of the median separation curve from almost vertical to almost horizontal more gradual.

Acknowledgment--The help of Joseph Curtis in carrying out the measurements is gratefully acknowledged.

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DIFFERENCE APPROXIMATIONS TO PARTIAL DERIVATIVES FOR UNEVEN SPACINGS IN THE NETWORK

Paul P. Rowe

Abstract--Difference expressions are developed which do not require even spacings in the network. These difference expressions are obtained by three different methods. The methods are Taylor's series expansion, operator calculus, and stencil mathematics. These difference expressions can then be applied in either the relaxation or iteration process. The errors involved in replacing the derivatives with these difference expressions are investigated. Most of these difference expressions are developed for use with the Laplace equation or the related equation, $h_{xx} + jh_{yy} = 0$.

Introduction--Many good difference expressions have been developed by previous workers for use with even or regular spacings in the network. However, an unusually fine network with a very large number of points is required in order to obtain even spacing for some problems. The necessity of a fine network to obtain even spacings may arise if there are (1) curved boundaries, (2) discontinuities within the boundaries, or (3) if the value of the function is known at many arbitrary points within the boundaries and it is desired to use these data. Therefore, the use of difference expressions which do not depend on equal spacings in the network will result in a saving of time in many problems.

Taylor's series expansion method--The following notation can be used $h = h(x, y)$ where h is a function of both x and y. The value of h at point $p(x, y)$ is given by a Taylor series expansion.

$$
\begin{aligned}
h(x, y) = {} & h(x_o, y_o) + h_x(x_o, y_o)(x - x_o) + h_y(x_o, y_o)(y - y_o) + (1/2!)[h_{xx}(x_o, y_o)(x - x_o)^2 \\
& + 2h_{xy}(x_o, y_o)(x - x_o)(y - y_o) + h_{yy}(x_o, y_o)(y - y_o)^2] + (1/3!)[h_{3x}(x_o, y_o)(x - x_o)^3 \\
& + 3h_{2xy}(x_o, y_o)(x - x_o)^2(y - y_o) + 3h_{x2y}(x_o, y_o)(x - x_o)(y - y_o)^2 \\
& + h_{3y}(x_o, y_o)(y - y_o)^3] + \dots \qquad (1)
\end{aligned}
$$

In (1) h_x is the first derivative of h with respect to x at $x = x_o$ and $y = y_o$ with similar meanings to h_y, h_{xx}, h_{yy}.

In order to save space in writing equations the following quantities will be written

$h(x_o, y_o)$ as h_o $h_x(x_o, y_o)$ as h_x $h_y(x_o, y_o)$ as h_y

and similarly for the other partial derivatives, also (Fig. 1)

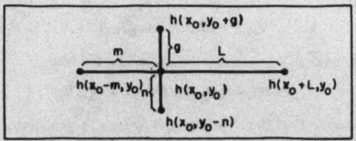

Fig. 1--Five points on an unevenly spaced network

$h(x_o + L, y_o)$ as h_1 $h(x_o, y_o + g)$ as h_2 $h(x_o - m, y_o)$ as h_3 $h(x_o, y_o - n)$ as h_4

At the point $x = x_o + L$, $y = y_o$ (1) becomes

$$h_1 = h_o + L\,h_x + L^2 h_{xx}/2! + L^3 h_{3x}/3! + \dots \qquad (2)$$

Similar equations exist for h_2, h_3, and h_4 as follows

$$h_2 = h_o + gh_y + g^2h_{yy}/2! + g^3h_{3y}/3! + \ldots \tag{3}$$

$$h_3 = h_o - mh_x + m^2h_{xx}/2! - m^3h_{3x}/3! + \ldots \tag{4}$$

$$h_4 = h_o - nh_y + n^2h_{yy}/2! - n^3h_{3y}/3! + \ldots \tag{5}$$

Eq. (2) can be multiplied by m, and (4) by L and added to obtain

$$mh_1 + Lh_3 = h_o(m + L) + (h_{xx}/2!)(mL^2 + Lm^2) + (h_{3x}/3!)(mL^3 - Lm^3) + \ldots \tag{6}$$

In a like manner (7) can be obtained from (3) and (5)

$$nh_2 + gh_4 = h_o(n + g) + (h_{yy}/2!)(ng^2 + gn^2) + (h_{3y}/3!)(ng^3 - gn^3) + \ldots \tag{7}$$

Eq. (6) and (7) become

$$h_{xx} = 2[mh_1 + Lh_3 - h_o(m + L)]/mL(m + L) \tag{8}$$

and

$$h_{yy} = 2[nh_2 + gh_4 - h_o(n + g)]/ng(n + g) \tag{9}$$

if h_{xx} and h_{yy} are solved for and terms containing third order and higher derivatives are neglected.

Using these approximations in the Laplace equation

$$h_{xx} + h_{yy} = 0 \tag{10}$$

there is obtained

$$[h_1/L(m + L) + h_3/m(m + L) + h_2/g(n + g) + h_4/n(n + g) - h_o(1/mL + 1/ng)] = 0 \tag{11}$$

Eq. (11) can be solved for h_o to obtain

$$h_o = \frac{h_1/(mL + L^2) + h_3/(mL + m^2) + h_2/(gn + g^2) + h_4/(gn + n^2)}{1/mL + 1/gn} \tag{12}$$

This is actually a generalization of the case where $m = L = g = n$, and for this case (12) becomes

$$h_o = (h_1 + h_2 + h_3 + h_4)/4 \tag{13}$$

which is a well-known equation used for a square network. The value of h_o converges to a stable one at a rate proportional to L^4 if (13) is used in either an iteration or a relaxation process.

The operator H can be defined as

$$H\,f(x_o, y_o) = f(x_o + L, y_o) + f(x_o - L, y_o) + f(x_o, y_o + L) + f(x_o, y_o - L) - 4f(x_o, y_o)$$

to obtain [MILNE, 1953, p. 131]

$$L^2\nabla^2 f(x, y) = H\,f(x, y) + O(L^4) \tag{14}$$

where the notation $O(L^4)$ means that the rate of convergence is proportional to L^4. Another way of stating this is to say that the truncation error is proportional to L^4. The truncation error is the error committed by neglecting the higher order terms in (6) and (7).

The terms in (6) and (7) which have been neglected in writing (8) and (9) are

$$(h_{3x}/3!)(mL^3 - Lm^3) + (h_{4x}/4!)(mL^4 + Lm^4) + (h_{5x}/5!)(mL^5 - Lm^5) + \ldots \tag{15}$$

and

$$(h_{3y}/3!)(ng^3 - gn^3) + (h_{4y}/4!)(ng^4 + gn^4) + (h_{5y}/5!)(ng^5 - gn^5) + \ldots \tag{16}$$

The assumption has been made in using Taylor's series that the derivatives of all orders exist; further let us assume that there is a derivative of order i that is numerically greater than or equal to any other derivative. The following inequalities are then true

$$\begin{aligned}&\Big|(h_{3x}/3!)\,mL^3 + (h_{4x}/4!)\,mL^4 + (h_{5x}/5!)\,mL^5 + \dots\dots - (h_{3x}/3!)\,Lm^3 + (h_{4x}/4!)\,Lm^4 \\ &\quad - (h_{5x}/5!)\,Lm^5 + \dots\dots\Big| \le \Big|h_{ix}[mL^3/3! + mL^4/4! + mL^5/5! + \dots\dots \\ &\quad - Lm^3/3! + Lm^4/4! - Lm^5/5! + \dots\dots]\Big| \quad \dots\dots\dots\dots (17)\end{aligned}$$

and

$$\begin{aligned}&\Big|(h_{3y}/3!)\,ng^3 + (h_{4y}/4!)\,ng^4 + (h_{5y}/5!)\,ng^5 + \dots\dots - (h_{3y}/3!)\,gn^3 + (h_{4y}/4!)\,gn^4 \\ &\quad - (h_{5y}/5!)\,gn^5 + \dots\dots\Big| \le \Big|h_{iy}\,[ng^3/3! + ng^4/4! + ng^5/5! + \dots\dots \\ &\quad - gn^3/3! + gn^4/4! - gn^5/5! + \dots\dots]\Big| \quad \dots\dots\dots\dots (18)\end{aligned}$$

The terms in brackets on the right side of (17) and (18) each contain two series. The second series in the right member of each is an alternating convergent series. The sum of such a series is always less than the first omitted term in magnitude.

The error E committed in using (8) can be written as $E = E_1 + E_2$ where E_1 is that due to the alternating series and is $E_1 \le |h_{ix}\ Lm^3/3!|$.

The first series in brackets on the right side of (17) can be written as

$$mL^3\,[1/3! + L/4! + L^2/5! + \dots\dots] \quad \dots\dots\dots\dots (19)$$

The numerical value of L can always be made less than unity (and actually is in practice) by a suitable stretching of the x axis; therefore the series in brackets in (19) is less than the following geometric series

$$1/6 + 2/6\cdot3 + 2^2/6\cdot3^2 + 2^3/6\cdot3^3 + \dots \quad \dots\dots\dots\dots (20)$$

whose sum is

$$S = (1/6)[1 - (2/3)^n]/(1 - 2/3) = 1/6\,[3/3 - (2/3)^n]/[(3 - 2)/3]$$

which finally results in

$$S = (1/6)\,[3 - 2^n/3^{n-1}]$$

and as $n \to \infty$, $S = 1/2$; therefore E_2 and error E are expressed by the inequalities

$$E_2 \le |(1/2!)\,h_{ix}mL^3| \qquad E \le |(1/2!)\,h_{ix}mL^3| \quad + \quad |(1/3!)\,h_{ix}Lm^3|$$

and the convergence in a relaxation or iteration process is proportional to $mL^3 + Lm^3$ and $gn^3 + ng^3$ for (8) and (9).

Define the operator H^1 as

$$\begin{aligned}H^1 f(x_0, y_0) &= \frac{f(x_0 + L, y_0)}{mL + L^2} + \frac{f(x_0 - m, y_0)}{mL + m^2} + \frac{f(x_0, y_0 + g)}{gn + g^2} \\ &\quad + \frac{f(x_0, y_0 - n)}{gn + n^2} - f(x_0, y_0)\ \left[\frac{1}{mL} + \frac{1}{gn}\right]\end{aligned}$$

and

$$H^1 f(x_0, y_0) = V^2 f(x_0, y_0) + O(mL^3 + Lm^3, gn^3 + ng^3)$$

The last term in this expression means that the rate of convergence is proportional to the quantities inside the bracket. A somewhat simpler equation to use than (12) is

$$h_o = \frac{h_1/L + h_2/g + h_3/m + h_4/n}{1/L + 1/g + 1/m + 1/n} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (21)$$

Eq. (21) can be obtained as follows: divide (2) by L and (4) by m and then add the resulting equations to get

$$h_1 + h_3 = h_o\,[1/L + 1/m] + (h_{xx}/2\,!)(L + m) + (h_{3x}/3\,!)(L^2 - m^2) + \ldots\ldots$$

An approximation to (L + m) h_{xx} can be obtained by neglecting third order and higher terms. This is

$$(L + m)\,h_{xx} = 2\,[h_1/L + h_3/m - h_o\,(1/L + 1/m)] \quad \ldots\ldots\ldots\ldots\ldots \quad (22)$$

In a like manner from equation (3) and (5) one can get

$$(g + n)\,h_{yy} = 2\,[h_2/g + h_4/n - h_o\,(\,1/g + 1/n)] \quad \ldots\ldots\ldots\ldots\ldots \quad (23)$$

Thus (21) can be obtained by replacing $h_{xx} + h_{yy} = 0$ by the approximations to (L + m) h_{xx} and (g + n) h_{yy}. Inequalities that correspond to (17) and (18) can be obtained. These inequalities are for the terms neglected in (22) and (23).

$$\left| h_{3x}L^2/3\,! + h_{4x}L^3/4\,! + h_{5x}L^4/5\,! + \ldots\ldots - h_{3x}m^2/3\,! + h_{4x}m^3/4\,! - h_{5x}m^4/5\,! + \ldots\ldots \right| \leq \left| h_{1x}\,[L^2/3\,! + L^3/4\,! + L^4/5\,! + \ldots\ldots - m^2/3\,! + m^3/4\,! - m^4/5\,! + \ldots\ldots] \right| \quad \ldots\ldots\ldots\ldots \quad (24)$$

$$\left| h_{3y}g^2/3\,! + h_{4y}g^3/4\,! + h_{5y}g^4/5\,! + \ldots\ldots - h_{3y}n^2/3\,! + h_{4y}n^3/4\,! - h_{5y}n^4/5\,! + \ldots\ldots \right| \leq \left| h_{1y}\,[g^2/3\,! + g^3/4\,! + g^4/5\,! + \ldots\ldots - n^2/3\,! + n^3/4\,! - n^4/5\,! + \ldots\ldots] \right| \quad \ldots\ldots\ldots\ldots \quad (25)$$

The error E_1 for the alternating series in (24) and (25) are respectively

$$E_1 \leq |(1/3!)m^2 h_{1x}| \qquad E_1 \leq |(1/3!)n^2 h_{1y}|$$

The non-altering series in brackets on the right of (24) is

$$L^2\,[\,1/3\,! + L/4\,! + L^2/5\,! + \ldots\ldots\ldots] \quad \ldots\ldots\ldots\ldots\ldots \quad (26)$$

The series in brackets in (26) is the same as in (19) so

$$E_2 \leq |(L^2/2\,!)\,h_{1x}| \qquad E = E_1 + E_2 \leq |h_{1x}\,[(\,1/3\,!)\,m^2 + (1/2\,!)\,L^2]\,|$$

and similarly the error E in replacing h_{yy} by (g + n) h_{yy} is

$$E \leq |\,h_{1y}\,[(1/3\,!)\,n^2 + (1/2\,!)\,g^2|$$

Eq. (21) is not an approximation to the Laplace equation but an approximation to

$$(L + m)\,h_{xx} + (g + n)\,h_{yy} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (27)$$

The rate of convergence of (21) to (27) is proportional to the squares of the distance between points in the net.

Eq. (21) can be used with quite satisfactory results if (27) becomes approximately $h_{xx} + h_{yy} = 0$ in that case. Another use for (21) is to start the solution of the Laplace equation in an iteration or relaxation process, and following a few traverses with (21) a change over to (12) can be made. Eq. (21) can also be used as a satisfactory approximation to $h_{xx} + jh_{yy} = 0$ if j is close to unity and unknown or if $j = (g + n)/(L + m)$. Eq. (22) and (23) can be solved for h_{xx} and h_{yy} and the results are

$$h_{xx} = [2/(L + m)]\,[h_1/L + h_3/m - h_0\,(1/L + 1/m)] \ldots\ldots\ldots\ldots \tag{28}$$

$$h_{yy} = [2/(g + n)]\,[h_2/g + h_4/n - h_0\,(1/g + 1/n)] \ldots\ldots\ldots\ldots \tag{29}$$

If these are taken as approximations to the Laplace equation, there is obtained

$$h_0 = \frac{h_1/(Lm + L^2) + h_3/(Lm + m^2) + h_2/(gn + g^2) + h_4/(gn + n^2)}{1/(Lm + L^2) + 1/(Lm + m^2) + 1/(gn + g^2) + 1/(gn + n^2)} \ldots\ldots \tag{30}$$

This equation has an error of the same magnitude as (21) and is more complicated but it is a direct approximation to the Laplace equation as is (13).

Operator calculus--A number of approximations to partial derivatives can be obtained by the use of operators. The particular approximation that one obtains depends on the operator used. It is possible to define four operators as follows

$$Uh(x_0, y_0) = h(x_0 + L, y_0) - h(x_0, y_0)$$

$$Vh(x_0, y_0) = h(x_0 - m, y_0) - h(x_0, y_0)$$

$$Wh(x_0, y_0) = h(x_0, y_0 + g) - h(x_0, y_0)$$

$$Zh(x_0, y_0) = h(x_0, y_0 - n) - h(x_0, y_0)$$

The operator U applied to the function at $x = x_0$ and $y = y_0$ gives the difference in the value of the function at $x_0 + L$ and y_0, and at x_0 and y_0; similarly for the other three operators.

The function $h(x_0 + L, y_0)$ can be expanded by Taylor's series and if the symbolic operators $D_x = \partial/\partial x$, $D_x^2 = \partial^2/\partial x^2$ are used, the expansion will be

$$h(x_0 + L, y_0) = h_0 + L\,D_x h_0 + L^2 D_x^2\,h_0/2! + L^3 D_x^3\,h_0/3! + L^4 D_x^4\,h_0/4! + \ldots$$

$$\doteq [1 + LD_x + L^2D_x^2/2! + L^3D_x^3/3! + L^4D_x^4/4! + \ldots\ldots]\,h_0 \ldots\ldots \tag{31}$$

where the notation $\doteq$ means equivalent to or symbolic equivalence. Then

$$U\,h_0 \doteq [1 + LD_x + L^2D_x^2/2! + L^3D_x^3/3! + L^4D_x^4/4! + \ldots\ldots]\,h_0 - h_0$$

The series in brackets is e^{LD_x} so it is possible to write a symbolic equation as follows

$$U \doteq e^{LD_x} - 1 \quad \text{or} \quad e^{LD_x} \doteq U + 1 \ldots\ldots\ldots\ldots \tag{32}$$

A similar development yields the following symbolic equations

$$e^{-mD_x} \doteq V + 1 \ldots\ldots\ldots\ldots \tag{33}$$

$$e^{gDy} \doteq W + 1 \ldots\ldots\ldots\ldots \tag{34}$$

$$e^{-nDy} \doteq Z + 1 \ldots\ldots\ldots\ldots \tag{35}$$

From (32) and (33) the following developments can be made

$$Ln e^{LDx} \doteq LD_x \doteq Ln(U + 1)$$

and

$$Ln e^{-mDx} \doteq -mDx \doteq Ln(V + 1)$$

and thus

$$-mL\,D_x^2 \doteq Ln(1 + U)\,Ln(1 + V) \ldots\ldots\ldots\ldots \tag{36}$$

The right side of (36) can be expanded in a power series to give

$$-mLD_x^2 \doteq [U - U^2/2 + U^3/3 - U^4/4 + \ldots\ldots][V - V^2/2 + V^3/3 - V^4/4 + \ldots\ldots] \doteq UV$$
$$- UV^2/2 + UV^3/3 - UV^4/4 - U^2V/2 + U^2V^2/4 - U^2V^3/6 + U^2V^4/8 + U^3V/3$$
$$- U^3V^2/6 + U^3V^3/9 - U^3V^4/12 - U^4V/4 + U^4V^2/8 - U^4V^3/12 + U^4V^4/16$$
$$- \ldots\ldots \doteq UV - (UV^2 + U^2V)/2 + (UV^3/3 + U^2V^2/4 + U^3V/3)$$
$$- (UV^4/4 + U^2V^3/6 + U^3V^2/6 + U^4V/4) + \ldots\ldots \qquad (37)$$

Eq. (37) can be solved for D_x^2 to give

$$D_x^2 \doteq (1/mL)\,[-UV + (UV^2 + U^2V)/2 - (UV^3/3 + U^2V^2/4 + U^3V/3)$$
$$+ (UV^4/4 + U^2V^3/6 + U^3V^2/6 + U^4V/4) - \ldots\ldots] \qquad (38)$$

Eq. (34) and (35) can be used in the same way to derive an expression for D_y^2. This results in

$$D_y^2 \doteq (1/gn)\,[-WZ + (WZ^2 + W^2Z)/2 - (WZ^3/3 + W^2Z^2/4 + W^3Z/3)$$
$$+ (WZ^4/4 + W^2Z^3/6 + W^3Z^2/6 + W^4Z/4) - \ldots\ldots] \qquad (39)$$

The more terms taken on the right side of equations (38) and (39) the more accurate the approximation to D_x^2 and D_y^2 becomes. However, some difficulty arises in interpretation of the higher terms for an uneven network and for an even network better equations than (38) and (39) can be obtained. Perhaps other operators can be defined which will give better results.

The greatest utility of (38) and (39) is in their application to lattice points that mark a boundary across which the mesh length changes in an otherwise even net (see Fig. 2). The interpretation of the higher terms is quite easy under these conditions.

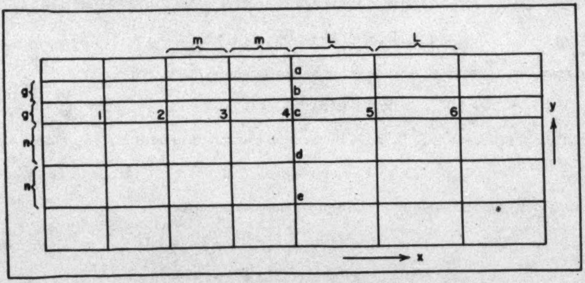

Fig. 2--Network with one change in each direction

The points a, b, c, d, and e are the points at which (38) is quite useful. The points 1, 2, 3, 4, 5, and 6 are the lattice points for which (39) is easily interpreted, and at the point designated by both 4 and c the approximation to Dx^2 and Dy^2 as given in (38) and (39) can be interpreted easily.

An approximation to the fourth order partial derivative $D_x^2D_y^2h = h_{xxyy}$ will now be obtained. This will be done mainly to illustrate some of the properties of stencils, a mathematical tool that is not as well known as it should be. For this particular approximation nine nodal or lattice points are used (see Fig. 3).

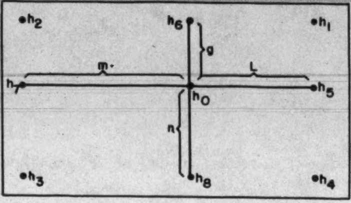

Fig. 3--Nine points on an unevenly spaced network

The value of the function at the outlying lattice points can be written in a Taylor's series. The notation following (2) is used. There are eight of these equations as follows

$$\begin{aligned} h_1 = {} & h_o + Lh_x + gh_y + (1/2\,!)\,[L^2h_{xx} + 2\,Lgh_{xy} + g^2h_{yy}] \\ & + (1/3\,!)\,[L^3h_{3x} + 3gL^2h_{xxy} + 3\,g^2Lh_{xyy} + g^3h_{3y}] \\ & + (1/4\,!)\,[L^4h_{4x} + 4L^3gh_{3x,y} + 6L^2g^2h_{xxyy} + 4Lg^3h_{x3y} + g^4h_{4y}] \\ & + (1/5\,!)\,[L^5h_{5x} + 5L^4gh_{4x,y} + 10L^3g^2h_{3x,2y} + 10L^2g^3h_{2x,3y} \\ & + 5Lg^4h_{x4y} + g^5h_{5y}] + \ldots\ldots \end{aligned} \tag{40}$$

$$\begin{aligned} h_2 = {} & h_o - mh_x + gh_y + (1/2\,!)\,[m^2h_{xx} - 2mgh_{xy} + g^2h_{yy}] \\ & + (1/3\,!)\,[-m^3h_{3x} + 3m^2gh_{xxy} - 3mg^2h_{xyy} + g^3h_{3y}] \\ & + (1/4\,!)\,[m^4h_{4x} - 4m^3gh_{3x,y} + 6m^2g^2h_{xxyy} - 4mg^3h_{x3y} + g^4h_{4y}] \\ & + (1/5\,!)\,[-m^5h_{5x} + 5m^4gh_{4x,y} - 10m^3g^2h_{3x,2y} + 10m^2g^3h_{2x,3y} \\ & - 5mg^4h_{x4y} + g^5h_{5y}] + \ldots\ldots \end{aligned} \tag{41}$$

$$\begin{aligned} h_3 = {} & h_o - mh_x - nh_y + (1/2\,!)\,[m^2h_{xx} + 2mnh_{xy} + n^2h_{yy}] \\ & + (1/3\,!)\,[-m^3h_{3x} - 3m^2nh_{xxy} - 3mn^2h_{xyy} - n^3h_{3y}] \\ & + (1/4\,!)\,[m^4h_{4x} + 4m^3nh_{3x,y} + 6m^2n^2h_{xxyy} + 4mn^3h_{x3y} + n^4h_{4y}] \\ & + (1/5\,!)\,[-m^5h_{5x} - 4m^4nh_{4x,y} - 10m^3n^2h_{3x,2y} - 10m^2n^3h_{2x,3y} \\ & - 5mn^4h_{x4y} - n^5h_{5y}] + \ldots\ldots \end{aligned} \tag{42}$$

$$\begin{aligned} h_4 = {} & h_o + Lh_x - nh_y + (1/2\,!)\,[L^2h_{xx} - 2Lnh_{xy} + n^2h_{yy}] \\ & + (1/3\,!)\,[L^3h_{3x} - 3L^2nh_{xxy} + 3Ln^2h_{xyy} - n^3h_{3y}] \\ & + (1/4\,!)\,[L^4h_{4x} - 4L^3nh_{3x,y} + 6L^2n^2h_{xxyy} - 4Ln^3h_{x3y} + n^4h_{4y}] \\ & + (1/5\,!)\,[L^5h_{5x} - 5L^4nh_{4x,y} + 10L^3n^2h_{3x,2y} - 10L^2n^3h_{2x,3y} \\ & + 5Ln^4h_{x4y} - n^5h_{5y}] + \ldots\ldots \end{aligned} \tag{43}$$

$$\begin{aligned} h_5 = {} & h_o + Lh_x + (1/2\,!)\,L^2h_{xx} + (1/3\,!)\,L^3h_{3x} + (1/4\,!)\,L^4h_{4x} \\ & + (1/5\,!)\,L^5h_{5x} + \ldots\ldots \end{aligned} \tag{44}$$

$$\begin{aligned} h_6 = {} & h_o + gh_y + (1/2\,!)\,g^2h_{yy} + (1/3\,!)\,g^3h_{3y} + (1/4\,!)\,g^4h_{4y} \\ & + (1/5\,!)\,g^5h_{5y} + \ldots\ldots \end{aligned} \tag{45}$$

$$\begin{aligned} h_7 = h_o &- mh_x + (1/2\,!)\, m^2 h_{xx} - (1/3\,!)\, m^3 h_{3x} + (1/4\,!)\, m^4 h_{4x} \\ &- (1/5\,!)\, m^5 h_{5x} + \ldots \ldots \end{aligned} \tag{46}$$

$$\begin{aligned} h_8 = h_o &- nh_y + (1/2\,!)\, n^2 h_{yy} - (1/3\,!)\, n^3 h_{3y} + (1/4\,!)\, n^4 h_{4y} \\ &- (1/5\,!)\, n^5 h_{5y} + \ldots \ldots \end{aligned} \tag{47}$$

Many of the terms in (40), (44), and (45) can be eliminated by subtracting (44) and (45) from (40). This results in the following

$$\begin{aligned} h_1 - h_5 - h_6 = &- h_o + Lgh_{xy} + (1/3\,!)\, [3L^2 gh_{xxy} + 3Lg^2 h_{xyy}] \\ &+ (1/4\,!)\, [4L^3 gh_{3x,y} + 6L^2 g^2 h_{xxyy} + 4Lg^3 h_{x3y}] \\ &+ (1/5\,!)\, [5L^4 gh_{4x,y} + 10L^3 g^2 h_{3x,2y} + 10L^2 g^3 h_{2x,3y} \\ &+ 5Lg^4 h_{x4y}] + \ldots \ldots \end{aligned} \tag{48}$$

Similar eliminations can be made by substrating (45) and (46) from (41), and (46) and (47) from (42), and finally subtracting (47) and (44) from (43). These operations give the following three equations

$$\begin{aligned} h_2 - h_6 - h_7 = &-h_o - mgh_{xy} + (1/3\,!)\, [3m^2 gh_{xxy} + 3mg^2 h_{xyy}] \\ &+ (1/4\,!)\, [-4m^3 gh_{3x,y} + 6m^2 g^2 h_{xxyy} - 4mg^3 h_{x3y}] \\ &+ (1/5\,!)\, [5m^4 gh_{4x,y} - 10m^3 g^2 h_{3x,2y} + 10m^2 g^3 h_{2x,3y} \\ &- 5mg^4 h_{x4y}] + \ldots \ldots \end{aligned} \tag{49}$$

$$\begin{aligned} h_3 - h_7 - h_8 = &-h_o + mnh_{xy} + (1/3\,!)\, [-3m^2 nh_{xxy} - 3mn^2 h_{xyy}] \\ &+ (1/4\,!)\, [4m^3 nh_{3x,y} + 6m^2 n^2 h_{xxyy} + 4mn^3 h_{x3y}] \\ &+ (1/5\,!)\, [-5m^4 nh_{4x,y} - 10m^3 n^2 h_{3x,2y} - 10m^2 n^3 h_{2x,3y} \\ &- 5mn^4 h_{x4y}] + \ldots \ldots \end{aligned} \tag{50}$$

$$\begin{aligned} h_4 - h_8 - h_5 = &-h_o - Lnh_{xy} + (1/3\,!)\, [-L^2 nh_{xxy} + 3Ln^2 h_{xyy}] \\ &+ (1/4\,!)\, [-4L^3 nh_{3x,y} + 6L^2 n^2 h_{xxyy} - 4Ln^3 h_{x3y}] \\ &+ (1/5\,!)\, [-5L^4 nh_{4x,y} + 10L^3 n^2 h_{3x,2y} - 10L^2 n^3 h_{2x,3y} \\ &+ 5Ln^4 h_{x4y}] + \ldots \ldots \end{aligned} \tag{51}$$

More terms can be eliminated among these equations by multiplying (48) by m and (49) by L and adding. The result is

$$\begin{aligned} m(h_1 - h_5 - h_6) + L(h_2 - h_6 - h_7) = &-h_o\,(m + L) + (1/3\,!)\; 3gmLh_{xxy}\,(m + L) \\ &+ (1/4\,!)\, [4mLgh_{3x,y}\,(L^2 - m^2) + 6\; mLg^2 h_{xxyy}\,(m + L)] \\ &+ (1/5\,!)\, [5mLgh_{4x,y}\,(m^3 + L^3) + 10mLg^2 h_{3x,2y}\,(L^2 - m^2) \\ &+ 10mLg^3 h_{2x,3y}\,(m + L)] + \ldots \ldots \end{aligned} \tag{52}$$

A similar equation can be obtained by multiplying (50) by L and (51) by m, thus

$$\begin{aligned} L(h_3 - h_7 - h_8) + m(h_4 - h_8 - h_5) = &-h_o\,(m + L) - (1/3\,!)\; 3mLnh_{xxy}\,(m + L) \\ &+ (1/4\,!)\, [4mLnh_{3x,y}\,(m^2 - L^2) + 6mLn^2 h_{xxyy}\,(m + L)] \end{aligned}$$

(continued on next page)

$$+ (1/5\,!)\,[-5mLnh_{4x,y}\,(m^3 + L^3) + 10mLn^2h_{3x,2y}\,(L^2 - m^2)$$
$$- 10mLn^3h_{2x,3y}\,(m + L)] + \ldots\ldots \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (53)$$

The final eliminations are made by dividing (52) by g and (53) by n and adding, thus

$$(m/g)(h_1 - h_5 - h_6) + (L/g)(h_2 - h_6 - h_7) + (L/n)(h_3 - h_7 - h_8)$$
$$+ (m/n)(h_4 - h_8 - h_5) = -h_o(m + L)(1/g + 1/n) + (6/4\,!)$$
$$mLh_{xxyy}\,(g + n)(m + L) + (1/5\,!)\,[10mLh_{3x,2y}\,(g + n)$$
$$(L^2 - m^2) + 10mLh_{2x,3y}\,(m + L)(g^2 - n^2)] + \ldots\ldots \qquad \ldots\ldots\ldots\ldots (54)$$

This can be divided through by mL and then if fifth order and higher terms are neglected, the result is

$$(1/4)h_{xxyy}\,(g + n)(m + L) = (1/gL)(h_1 - h_5 - h_6) + (1/gm)$$
$$(h_2 - h_6 - h_7) + (1/mn)(h_3 - h_7 - h_8) + (1/nL)$$
$$(h_4 - h_8 - h_5) + h_o\,(1/L + 1/m)(1/g + 1/n) \ldots\ldots\ldots\ldots\ldots\ldots (55)$$

This equation can be solved for $h_{xxyy} = D_x^2\, D_y^2 = \partial^4 h/\partial x^2\, \partial y^2$

This approximation will then be

$$h_{xxyy} = [4/(g + n)(m + L)]\,[h_1/gL + h_2/gm + h_3/mn + h_4/nL - (h_5/L)(1/g + 1/n)$$
$$- (h_6/g)(1/L + 1/m) - (h_7/m)(1/g + 1/n) - (h_8/n)(1/L + 1/m)$$
$$+ h_o(1/L + 1/m)(1/g + 1/n)] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (56)$$

Stencil mathematics--It is possible to define an operator θ such that when θ operates on h_o, the result is the right-hand side of (56). Associated with this is the point pattern shown in Figure 3 and also the following stencil.

$$\theta = \frac{4}{(g + n)(m + L)}\;\begin{array}{|c|c|c|}\hline 1/gm & -(1/g)(1/L + 1/m) & 1/gL \\ \hline -(1/m)(1/g + 1/n) & (1/L + 1/m)(1/g + 1/n) & -(1/L)(1/g + 1/n) \\ \hline 1/mn & -(1/n)(1/L + 1/m) & 1/nL \\ \hline \end{array} \; .(57)$$

If A and B are stencils and

$$A = \begin{array}{|c|c|c|}\hline a_{-1,1} & a_{o,1} & a_{1,1} \\ \hline a_{-1,o} & a_{o,o} & a_{1,o} \\ \hline a_{-1,-1} & a_{o,-1} & a_{1,-1} \\ \hline \end{array} \qquad\qquad B = \begin{array}{|c|c|c|}\hline b_{-1,1} & b_{o,1} & b_{1,1} \\ \hline b_{-1,o} & b_{o,o} & b_{1,o} \\ \hline b_{-1,-1} & b_{o,-1} & b_{1,-1} \\ \hline \end{array}$$

Then if C = A + B, $c_{ij} = a_{ij} + b_{ij}$ for the three by three stencil above. If D = AB, then $d_{pr} = \Sigma\, a_{ij}b_{st}$ where p = i + S and r = j + t.

The stencil on the right side of (57) can be factored into two separate stencils if use is made of the multiplication properties of stencils. The result is

$$\theta = \frac{2}{m + L} \begin{array}{|c|c|c|} \hline 1/M & -(1/L + 1/m) & 1/L \\ \hline \end{array} \; \frac{2}{(g + n)} \begin{array}{|c|} \hline 1/g \\ \hline -(1/g + 1/n) \\ \hline 1/n \\ \hline \end{array} \quad \ldots . (58)$$

A factored stencil is of value when a computing machine using punched cards or continuous tape is used, and the data are available to the machine only in a linear sequence.

An approximation to h_{xy} will be obtained. This will be done by a different method. The operator Φ can be defined as follows (see Fig. 3)

$$\Phi h_o = a[h_1 + h_2 + h_3 + h_4] + b[h_5 + h_6 + h_7 + h_8] + ch_o \quad \ldots\ldots\ldots\ldots (59)$$

This operator can be represented by the stencil

$$\Phi = \begin{array}{|c|c|c|} \hline a & b & a \\ \hline b & c & b \\ \hline a & b & a \\ \hline \end{array} \quad \ldots\ldots\ldots\ldots\ldots\ldots (60)$$

The right side of (60) can be factored into

$$\begin{array}{|c|c|c|} \hline a & b & a \\ \hline \end{array} \; \begin{array}{|c|} \hline 1 \\ \hline b/a \\ \hline 1 \\ \hline \end{array} = \begin{array}{|c|c|c|} \hline a & b & a \\ \hline b & b^2/a & b \\ \hline a & b & a \\ \hline \end{array} \quad \ldots\ldots\ldots\ldots (61)$$

if

$$c = b^2/a \quad \ldots\ldots\ldots\ldots\ldots\ldots (62)$$

The terms in brackets in (59) can be expanded by Taylor's series (see (40) through (47)). The expansion of these terms will be made with the use of the following operator notation.

$h_x = D_x h_o$, $h_y = D_y h_o$, $h_{xy} = D_x D_y h_o$, $h_{xx} = D_x^2 h_o$

$h_{yy} = D_y^2 h_o$, $h_{xxy} = D_x^2 D_y h_o$, $h_{xyy} = D_x D_y^2 h_o$, and similar expressions for higher order terms.

If (59) is expanded with the aid of this notation and terms collected, it becomes

$$\begin{aligned} \Phi h_o = {} & a\,[4h_o + 2(L - m)D_x h_o + (2/2\,!)(L^2 + m^2)\,D_x^2 h_o + (2/3\,!)(L^3 - m^3)D_x^3 h_o \\ & + 2(g - n)D_y h_o + (g - n)(L - m)D_x D_y\, h_o + (1/2\,!)(g - n)(L^2 + m^2)\,D_x^2 D_y h_o \\ & + (1/3\,!)(g - n)(L^3 - m^3)\,D_x^3 D_y h_o + (2/2\,!)(g^2 + n^2)D_y^2 h_o + (1/2\,!)\,(g^2 + n^2) \\ & (L - m)D_x D_y^2 h_o + (1/2\,!\,2\,!)(g^2 + n^2)(L^2 + m^2)D_x^2 D_y^2 h_o + (1/2\,!\,3\,!)(g^2 + n^2) \\ & (L^3 - m^3)D_x^2 D_y^3 h_o + (2/3\,!)(g^3 - n^3)D_y^3 h_o + (1/3\,!)(g^3 - n^3)(L - m)D_x D_y^3 h_o \\ & + (1/2\,!\,3\,!)(g^3 - n^3)(L^2 + m^2)D_x^2 D_y^3 h_o + (1/3\,!\,3\,!)(g^3 - n^3)(L^3 - m^3) \\ & D_x^3 D_y^3 h_o + \ldots\ldots] + b\,[4h_o + (L - m)D_x h_o + (1/2\,!)(L^2 + m^2)D_x^2 h_o + (1/3\,!) \\ & (L^3 - m^3)\,D_x^3 h_o + (g - n)D_y h_o + (1/2\,!)(g^2 + n^2)D_y^2 h_o + (1/3\,!) \\ & (g^3 - n^3)D_y^3 h_o + \ldots\ldots] + ch_o \quad \ldots\ldots\ldots\ldots (63) \end{aligned}$$

Formally h_0 can be cancelled from both sides of (63), and

$$\begin{aligned}\Phi \doteq\ & a\,[4 + 2(L - m)D_x + (2/2!)(L^2 + m^2)D_x^2 + (2/3!)(L^3 - m^3)D_x^3 + 2(g - n)D_y \\ & + (2/2!)(g^2 + n^2)D_y^2 + (2/3!)(g^3 - n^3)D_y^3 + (1/2!)(g - n)(L^2 + m^2)D_x^2D_y \\ & + (1/3!)(g - n)(L^3 - m^3)D_x^3D_y + (1/2!)(g^2 + n^2)(L - m)D_xD_y^2 + (1/2!\,2!) \\ & (g^2 + n^2)(L^2 + m^2)D_x^2D_y^2 + (1/2!\,3!)(g^2 + n^2)(L^3 - m^3)D_x^3D_y^2 + \ldots\ldots] \\ & + b\,[4 + (L - m)D_x + (1/2!)(L^2 + m^2)D_x^2 + (1/3!)(L^3 - m^3)D_x^3 + (g - n)D_y \\ & + (1/2!)(g^2 + n^2)D_y^2 + (1/3!)(g^3 - n^3)D_y^3 + \ldots\ldots] + c \qquad (64)\end{aligned}$$

The sum of the purely numerical terms can be reduced to zero if the following condition is imposed.

$$4a + 4b + c = 0 \qquad (65)$$

Eq. (62) can be substituted into (65) to obtain

$$4a + 4b + b^2/a = 0$$

This when multiplied through by a becomes

$$4a^2 + 4ab + b^2 = 0 \qquad (66)$$

The quadratic formula can be used to solve (66) for b in terms of a. The result is as follows

$$b = (-4a \pm \sqrt{16a^2 - 16a^2})/2$$

or

$$b = -2a \qquad (67)$$

The value of b is -2 if a is arbitrarily set equal to one and c by (62) is equal to four. Eq. (64) takes on the following form under these conditions.

$$\begin{aligned}\Phi \doteq\ & (g - n)(L - m)D_xD_y + (1/2!)(g - n)(L^2 + m^2)D_x^2D_y + (1/3!)(g - n) \\ & (L^3 - m^3)D_x^3D_y + (1/2!)(g^2 + n^2)(L - m)D_xD_y^2 + (1/2!\,2!)(g^2 + n^2) \\ & (L^2 + m^2)D_x^2D_y^2 + (1/2!\,3!)(g^2 + n^2)(L^3 - m^3)D_x^3D_y^2 + (1/3!)(g^3 - n^3) \\ & (L - m)D_xD_y^3 + (1/2!\,3!)(g^3 - n^3)(L^2 + m^2)D_x^2D_y^3 + (1/3!\,3!)(g^3 - n^3) \\ & (L^3 - m^3)D_x^3D_y^3 + \ldots\ldots \qquad (68)\end{aligned}$$

The conditions imposed on a, b, and c cause the stencil in (60) to be as follows

$$\begin{array}{|c|c|c|}\hline a & b & a \\ \hline b & c & b \\ \hline a & b & a \\ \hline\end{array} = \begin{array}{|c|c|c|}\hline 1 & -2 & 1 \\ \hline -2 & 4 & -2 \\ \hline 1 & -2 & 1 \\ \hline\end{array} = \begin{array}{|c|c|c|}\hline 1 & -2 & 1 \\ \hline\end{array} \quad \begin{array}{|c|}\hline 1 \\ \hline -2/1 \\ \hline 1 \\ \hline\end{array} \qquad (69)$$

MILNE [1953, p. 133] defines the operator N^2 as

$$N^2 = 2(X - H) = \begin{array}{|c|c|c|}\hline 1 & -2 & 1 \\ \hline -2 & 4 & -2 \\ \hline 1 & -2 & 1 \\ \hline\end{array} \qquad (70)$$

The operators X and H are represented by the following stencils

$$X = (1/2)\begin{array}{|c|c|c|}\hline 1 & & 1 \\ \hline & -4 & \\ \hline 1 & & 1 \\ \hline \end{array} \qquad H = \begin{array}{|c|c|c|}\hline & 1 & \\ \hline 1 & -4 & 1 \\ \hline & 1 & \\ \hline \end{array}$$

The operation N^2h is a good approximation to h_{xxyy} if $g = n$ and $L = m$. That this is true can be seen from (68). This approximation can be shown to be under these conditions plus $L = g$.

$$N^2 = L^4 D_x^2 D_y^2 + O(L^6)$$

Eq. (68) can be factored to give the expression

$$\Phi \doteq [(g - n)D_y + (1/2\,!)(g^2 + n^2)D_y^2 + (1/3\,!)(g^3 - n^3)D_y^3 + (1/4\,!)(g^4 + n^4)D_y^4 + \ldots\ldots]$$
$$[(L - m)D_x + (1/2\,!)(L^2 + m^2)D_x^2 + (1/3\,!)(L^3 - m^3)D_x^3 + (1/4\,!)(L^4 + m^4)D_x^4 + \ldots\ldots]$$

This can be expanded as follows

$$\begin{aligned}\Phi \doteq {} & [(g - n)D_y + (1/2\,!)g^2D_y^2 + (1/3\,!)g^3D_y^3 + (1/4\,!)g^4D_y^4 + \ldots\ldots \\ & + (1/2\,!)n^2D_y^2 - (1/3\,!)n^3D_y^3 + (1/4\,!)n^4D_y^4 - \ldots\ldots][(L - m)D_x \\ & + (1/2\,!)L^2D_x^2 + (1/3\,!)L^3D_x^3 + (1/4\,!)L^4D_x^4 + \ldots\ldots + (1/2\,!)m^2D_x^2 \\ & - (1/3\,!)m^3D_x^3 + (1/4\,!)m^4D_x^4 - \ldots\ldots]\end{aligned} \qquad (71)$$

The operator Φ becomes an approximation to $(g - n)(L - m)D_xD_y$ if all but the first term in each bracket is neglected.

There are two series in each of the two brackets of (71). These four are by changing notations, letting each operator operate on h_o, and neglecting the first term in each series.

$$(1/2\,!)g^2h_{yy} + (1/3\,!)g^3h_{3y} + (1/4\,!)g^4h_{4y} + (1/5\,!)g^5h_{5y} + \ldots\ldots \qquad (72)$$

$$(1/2\,!)n^2h_{yy} - (1/3\,!)n^3h_{3y} + (1/4\,!)n^4h_{4y} - (1/5\,!)n^5h_{5y} + \ldots\ldots \qquad (73)$$

$$(1/2\,!)L^2h_{xx} + (1/3\,!)L^3h_{3x} + (1/4\,!)L^4h_{4x} + (1/5\,!)L^5h_{5x} + \ldots\ldots \qquad (74)$$

$$(1/2\,!)m^2h_{xx} - (1/3\,!)m^3h_{3x} + (1/4\,!)m^4h_{4x} - (1/5\,!)m^5h_{5x} + \ldots\ldots \qquad (75)$$

The error in neglecting the series in (73) is

$$E_{yl} \leq |n^2 h_{ly}/2\,!|$$

where h_{ly} is the partial derivative with the largest numerical value. Similar for (75) the error in neglecting this series is

$$E_{xl} \leq |m^2 h_{lx}/2\,!|$$

Two inequalities can be written using (72) and (74). They are

$$\begin{aligned}& |(1/2\,!)g^2h_{yy} + (1/3\,!)g^3h_{3y} + (1/4\,!)g^4h_{4y} + (1/5\,!)g^5h_{5y} + \ldots\ldots| \\ \leq {} & |h_{ly}[(1/2\,!)g^2 + (1/3\,!)g^3 + (1/4\,!)g^4 + (1/5\,!)g^5 + \ldots\ldots]|\end{aligned} \qquad (76)$$

$$\begin{aligned}& |(1/2\,!)L^2h_{xx} + (1/3\,!)L^3h_{3x} + (1/4\,!)L^4h_{4x} + (1/5\,!)L^5h_{5x} + \ldots\ldots| \\ \leq {} & |h_{lx}[(1/2\,!)L^2 + (1/3\,!)L^3 + (1/4\,!)L^4 + (1/5\,!)L^5 + \ldots\ldots]|\end{aligned} \qquad (77)$$

As g and L are both less than one the following inequalities can be written

$$1/2! + (1/3!)g + (1/4!)g^2 + (1/5!)g^3 + \ldots\ldots \leq 1/2 + 1/2^2 + 1/2^3 + 1/2^4 + \ldots\ldots \quad (78)$$

The sum S on the right of (78) is

$$S = (1/2)[1 - (1/2)^n/(1 - 1/2) = 1 - (1/2)^n$$

and as $n \rightarrow \infty$, $S \rightarrow 1$, so

$$\left| h_{1y}\, g^2 [1/2! + (1/3!)g + (1/4!)g^2 + (1/5!)g^3 + \ldots\ldots] \right| \leq \left| h_{1y}\, g^2 \right|$$

and

$$E_{y2} \leq \left| h_{1y}\, g^2 \right|$$

The same procedure similarly shows that E

$$E_{x2} \leq \left| h_{1x}\, L^2 \right|$$

The total error in representing $(g - n)(L - m)D_xD_yh_o$ by Φh_o is

$$(E_{y1} + E_{y2})(E_{x1} + E_{x2}) = (E_y)(E_x)$$

$$\leq \left| [(1/2!)n^2h_{1y} + g^2h_{1y}]\,[(1/2!)m^2h_{1x} + L^2h_{1x}] \right| = \left| [(1/2!)n^2 + g^2]\,[(1/2!)m^2 + L^2]\,h_{1y}\,h_{1x} \right|$$

The results obtained here show that it is possible to derive many different approximations to any given partial derivative. The best approximation in any given case depends upon the geometry of the network. Care must be exercised in applying any particular approximation to make sure that the approximation selected is applicable to the network under consideartion. For example, the operator $\Phi/(g - n)(L - m)$ becomes a poor approximation to D_xD_y if either g = n or m = L or if both conditions exist. Another example is in the use of (21) which is an approximation to $(L + m)h_{xx} + (g + n)h_{yy} = 0$.

Eq. (21) is not a good approximation to the Laplace equation

$$h_{xx} + h_{yy} = 0$$

if the ratio $(g + n)/(L + m)$ is significantly different from unity. In a like manner if $(g + n)/(L + m)$ is quite different in value from the value of j then (21) is not a good approximation to

$$h_{xx} + jh_{yy} = 0$$

However, (21) is an easy equation to apply in an iteration process and converges with reasonable rapidity. It is a good equation to use where the proper conditions prevail. As was stated previously, operators that are different than those used here may result in better approximations or some that are equally as good but which may be easier to apply. Thus, additional work should be done with operators to see if better approximations can be obtained.

As an example one may define the three operators

$$K = U + V \qquad N = U - V \qquad \text{and} \qquad Q = 2UV$$

The use of stencils shows that K = -Q. With these or other operators it may be possible to develop a more rapidly converging series than that given in (38).

The coefficients of the terms in the difference approximations can be considered as weighting factors. Each weighting factor becomes unity in the case where the spacings in the network are all the same. As a general rule the sum of the coefficients of h_i 's (where i = 1, 2, ... , n) divided by the coefficient of h_o results in either 1 or -1 depending on whether there is an equal sign between h_o and the h_i 's or not.

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THE STATUS OF WATER SPREADING FOR GROUND-WATER REPLENISHMENT

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Abstract--Methods of spreading water on land surfaces and by injection are reviewed and some results given. Some localities utilizing or contemplating the use of water spreading to replenish ground-water supplies are mentioned. Included are: (1) developments in vegetative, chemical and mechanical treatments to increase infiltration rate; (2) shaft, trench, and pit injection methods which cut through less pervious soil and inject water into aquifers; and (3) operational procedures such as cultural methods, length of wetting and drying periods, and surface head. Soil-water movements are described and interpreted in the light of the Darcy equation. Limitations in the use of treatments based on the surface soil and stratigraphy are described. Solutions to some problems and research directed toward existing needs are mentioned. A strip system and rotational system of spreading water based on an infiltration rate-percolation rate ratio are described. The strip system uses portions of an area and it is conceived that as much water may infiltrate as using the entire area. Surface soil treatment to increase this ratio may result in additional benefits. Land between flooded portions might be farmed or used for other purposes. This system visualizes a 'subsurface lake.' In the rotation system some portions will be flooded while infiltration rates remain high and other portions will be drying for recovery in infiltration rate. Tools to determine the suitability and characteristics of a proposed spreading area, such as soil surveys, laboratory tests of water and soil, well logs, jetting, cable tool test holes and infiltrometers are discussed. Examples are given of water spreading grounds constructed on sites selected by the use of these tools.

Introduction

The artificial replenishment of ground water is known as water spreading. Water may be spread over land to infiltrate through the soil surface and percolate to the ground-water table. The less common approach employs shafts, pits, trenches, or wells to inject water directly into aquifers to recharge ground-water supplies. The objective is to salvage, at minimum cost, water which wastes to the ocean, to salt lakes, and to locations where recharge is not as necessary or is lost through evaporation and excessive consumptive use.

This paper reviews developments in water spreading and discusses some of the solutions to present problems and research directed toward future needs. Research reported herein is being conducted concurrently in the laboratory and in the field by the Western Soil and Water Management Section, Soil and Water Conservation Research Branch, Agricultural Research Service, United States Department of Agriculture in cooperation with the Kern County Land Co., North Kern Water Storage District, the California State Division of Water Resources, and the California Agricultural Experiment Station. Reference is made to other research also aimed at developing soil and water treatments and field operational procedure designed to increase the rate at which water enters the soil and moves through the profile.

Arizona, Arkansas, California, Louisiana, Nevada, New Mexico, Ohio, Oklahoma, and Texas are examples of states where pumping is depleting the underground water. In these and other states where spreading is developing or being considered, the capacity of depleted ground-water basins must be determined and steps taken to replenish them.

Water spreading has been used largely in the semi-arid West, notably California with 87 projects, in connection with replenishment for irrigation, municipal, and industrial supplies. Many ground-water reservoirs have a greater capacity than the largest artificial surface reservoir yet few are fully utilized to store flood water for later use. Few undeveloped economical surface reservoir sites remain in the West. The U. S. Geological Survey has estimated that between the depths of ten and 200 ft below ground surface there are approximately 120,000,000 ac ft of ground water storage capacity in California's Central Valley [POLAND, DAVIS, OLMSTED and KUNKEL, 1951]. This is more than four times the surface storage visualized in the Central Valley Basin plan by the U. S. BUREAU of RECLAMATION [1949]. Forty-four subsurface reservoirs in California, which include most of the major reservoirs, show water deficiencies. The California Division of Water Resources and the U. S. Bureau of Reclamation are formulating plans for the use of these large subsurface reservoirs. Over one-half the water used in the San Joaquin Valley is pumped and deficiencies are increasing with expanded developments. Storage of water in subsurface reservoirs can supplement surface storage [CLENDENEN, 1955].

Water spreading in the Middle West and East is used largely to sustain industrial and domestic supplies. It may also be destined to supply underground water for ultimate irrigation during drouth periods in humid areas.

Some previous work--Examples of existing water-spreading projects in the Midwest and East are: (1) the infiltration pit constructed by Peoria industries and Illinois State Water Survey on the bank of the Illinois River at Peoria; (2) in Nassau County in Long Island, New York, storm runoff water has been collected from built-up areas and spread on recharge basins since 1936; (3) in Dayton, Ohio, dams on the Mad River are used to raise the water to a point where it can be brought into Rohwer Island and run through meandering canals over the sandy surface to infiltrate and raise the water table contacted by wells.

On pits, basins and canals nothing finer-textured than sand generally is used as a surface layer. To keep the soil surface open, surface crusts that develop are broken lightly with a harrow at both the Long Island and Dayton projects. Mixing of the clogging material with the soil is avoided. Scraping and removal of the top layer and replacement with sand are usually required in the fall at Dayton depending on the silt content of the Mad River. A layer of soil four to six inches deep is usually removed from the recharge basins and replaced with sand and grits once in several years at Long Island.

Consideration is being given to the use of material coarser than sand as a top layer replacement. A top layer of pea gravel placed on the Peoria infiltration pit for the 1955 run approximately doubled infiltration rates obtained previously with a top layer of sand. The pea gravel appears to serve as an effective filter and yet retains sufficient porosity for rapid infiltration.

Early successful water spreading in Southern California was effected by erecting temporary diversions to debris cones at the mouths of canyons [MITCHELSON and MUCKEL, 1937]. The size of areas devoted to spreading was of little concern as such areas were generally considered wastelands. The problem was one of diversion and protection from flood flows and the bypassing of flows laden heavily with sediment [MITCHELSON, 1949]. Whenever possible porous areas are selected either in the immediate vicinity where replenishment is desired or hydraulically upslope.

Spreading methods used singly or in combination are: (1) the basin method, (2) the furrow method, (3) the flooding method, and (4) the use of pits and shafts. The basin method impounds water in a series of small basins formed by dikes and so arranged as to permit submergence of the entire area. The overtopping variation of the basin method consists of binding nonerosive material, such as rock, together with heavy hog wire to form a dike. Dike elevations insure water backing up from one dike to the toe of the dike above thus submerging the entire area. The furrow or ditch method conveys water in shallow, flat-bottomed, closely-spaced ditches, sloped to prevent silt deposition and reduction in infiltration rate. The flooding method consists of passing water overland in a thin sheet either in natural stream channels or other areas. Sufficient controls are employed to prevent collection of the water in small streams. Shafts or pits are sometimes sunk to inject water underground but more frequently use is made of abandoned gravel pits, wells, or other existing holes. Silty water is avoided. Only isolated installations have been reported as being successful. These methods have been described by MUCKEL [1948].

LAVERTY [1953] and BAUMANN [1952, 1955] have advanced the theoretical and practical aspects of recharging ground-water supplies by reporting on spreading on basins overlying open aquifers and by injection spreading. Through these methods the Los Angeles County Flood Control District has added some 1,200,000 ac ft to ground water from 1915 to 1955. This District with several cooperators has also shown that it is possible to inject water into wells to establish pressure mounds to halt the intrusion of sea water and protect usable ground water. The experimental injection work at Manhattan Beach was conducted with California State funds under jurisdiction of the State Water Resources Board.

Good infiltration rates averaging about 3.6 ft per day at the Saticoy Spreading Grounds in Ventura County have been maintained for a long time on a finer textured soil than represented by most of the Southern California spreading areas. The soil is a fine sandy loam with a good native grass cover. Roots extend almost to the underlying sand. Water from the Santa Clara River is not spread when it exceeds a turbidity of 25 ft^3 of sediment per acre foot of water. Early work in this area is described by FREEMAN [1936].

Progress is being made on reclaiming and spreading sewage effluents. When a final sewage effluent was spread, infiltration rates of two feet per day occurred on a coarse soil [STONE and GARBER, 1951], and 0.5 ft/day on a medium textured soil [UNIVERSITY OF CALIFORNIA, 1953], and reports that a bacteriologically safe water can be produced from settled sewage or final effluents if the liquid passes through at least four feet of the medium textured soil.

The California State Division of Water Resources with the Agricultural Research Service is conducting an inventory on water spreading activities and experimental work in the State to be published in the near future [BANKS, RICHTER, COE, McPARTLAND, KRETSINGER, in press].

Terms--The terms used follow:

Soil permeability--The rate or readiness with which a soil transmits water.

Infiltration rate--The rate at which water flowing or impounded at a shallow depth enters the soil at any instant.

Potential infiltration rate--The rate at which flowing or impounded water at a shallow depth can enter the soil at any instant when conditions beneath the surface do not limit flow.

Percolation rate--The rate of downward flow of water through a depth of soil.

Surface head--Depth of water on the soil surface. Surface head is part of the hydraulic head which motivates flow.

Hydraulic head--The elevation with respect to a standard datum at which water stands in a manometer connected to the point in question in the soil.

The problems--The problems of recharge may be divided into four main types by site conditions: (1) where surface and subsurface conditions permit the rapid movement of water to the ground-water table; (2) where surface conditions limit the rate of flow to the ground-water table; (3) where subsurface conditions limit the rate of inflow; and (4) where both surface and subsurface conditions limit inflow. In many areas in the West soils range from sandy loams to clay loams and in some instances are underlain by hardpans. These soils do not absorb water rapidly, yet replenishment of ground water is a necessity to support present irrigated agricultural and other developments and predicted expansion. The San Joaquin Valley in California is an example of areas where water spreading on relatively impervious soils is practiced and involves problems 2, 3, or 4 listed above. The average infiltration rate is about 0.5 ft/day for a period of submergence of four or more months on newly prepared spreading areas larger than 16 ac on either Hesperia sandy loam or Exeter sandy loam. Under prolonged submergence the infiltration rate initially declines due to dispersion, recovers as entrapped air is dissolved, and then declines as clogging gases, liquids and solids are secreted by microorganisms [CHRISTIANSEN and MAGISTAD, 1944]. Swelling soil colloids and the settling of material from the water supply also cause a decline in infiltration rate. Average infiltration rates of 1.5 ft/day or higher are desired for a spreading season in the Valley to reduce the area of valuable farm land devoted to spreading and to localize water where needed. A spreading season may last up to several months.

Procedure

Field experiments are performed on Hesperia sandy loam near Wasco and on Exeter sandy loam near Minter Field, California. The upper subsoil layers of Hesperia sandy loam are finer in texture than the topsoil due to stratification. Exeter sandy loam is underlain by discontinuous hardpans at variable depths ranging generally from 36 to 48 inches.

Laboratory experiments are being conducted by the Agricultural Research Service at Bakersfield, California on these same soils as well as on water and soil samples obtained from field experiments. Well water is used in infiltrometers and small test ponds when canal water is not available. Canal water originating from the Kern River is used occasionally in small test ponds and exclusively on larger areas. Both waters are satisfactory, although higher infiltration rates are obtained with the well water. In addition to numerous small infiltrometers and test ponds for experimental purposes there are one-half acre basins, larger basins which are parts of actual spreading areas and trenches. Piezometers are employed to determine soil-water movements, to chart the development of perched water tables and to record losses in hydraulic head. Water supplied is measured by meters, weirs, and gates.

The Kern County Land Company and North Kern Water Storage District operate spreading areas at Minter Field, Poso, Rosedale and Switchfield that comprise about 1800 acres. Of this acreage about 700 acres are in pasture which is flooded for deep percolation whenever sufficient water is available. These agencies have developed an extensive experimental setup which includes mechanical treatments such as ripping and the treatment of basins with organic residues, grasses and chemicals. Four trenches or pits are under observation Experimental treatments are studied on 42 square one-acre basins. A network of piezometers has been installed in conjunction with many of the field setups. A progress report has been prepared by the Kern County Land Company covering development of the spreading areas and containing experimental data for the period January 1952-October 1954 [CAMPBELL, 1955].

Water and surface soil treatments on small areas--Treatments of soil and water started in 1936 by the North Kern Water Storage District and continued since 1944 under a cooperative program on small test ponds include gypsum, calcium chloride, detergents, removal of crusts, removal of topsoil, cultivation, and introduction of various grasses and organic residues. During the last few years experiments have included the use of soil conditioners to find treatments that might increase surface permeability immediately. Conditioners have been applied in powder form. Treatments of soil and water are designed to enlarge soil pores, develop stable aggregates and promote continuity of large pores through less pervious soil layers. Water and soil are also treated to prevent chemical dispersion of soil particles.

Soil-water movements are described and discussed in general and in the light of the Darcy equation. Tools for characterizing the suitability and feasibility of an area for water spreading are mentioned and exemplified.

Results and interpretation

Soil and water treatments on small areas--The experimental setup and results of cooperative studies conducted by the Agricultural Research Service through 1953 are discussed in detail by SCHIFF [1954]. A summary of these results and results obtained during 1954 are shown in Table 1. Outstanding increases in infiltration rates were obtained with cotton gin trash and Bermuda grass. The benefits due to microbial decomposition of cotton gin trash following wetting and drying (incubation) are described by BLISS and JOHNSON [1952]. Different organic residues and grasses may be more readily available or suitable in other areas. Some of the treatments mentioned under procedure and now relegated to the background locally, may be useful elsewhere. Quality of water continues to receive attention. The use of chemicals such as gypsum on small ponds resulted in somewhat higher infiltration rates. Where sodium is a major problem benefits may be expected through the use of gypsum.

Table 1 also shows that high infiltration rates were obtained with soil conditioners on the first test run. Grasses take time to become established and organic residues require time for adequate decomposition before producing high infiltration rates. Handling and incorporating large quantities of cotton gin trash have proven expensive. Grasses and cotton-gin trash treatments initiated several years ago are still giving high infiltration rates. Evidence in Table 1 indicates less longevity of benefits with soil conditioners. The original superiority of soil conditioners may not overcome their lack of longevity. Occasional applications of a soil conditioner are a possibility which must be evaluated in the light of the negative effects of additional cultural operations, benefits and economics. A treatment combining a soil conditioner and grass might lead to immediate and prolonged benefits, particularly for finer textured soil. A definite factor in longevity appears to be the silt content of the water being spread and its clogging effect on settling. Clear water is used in all small-pond tests. Observations on large areas indicate that grasses maintain a more friable and open condition on the surface than do present soil conditioners, particularly as the sediment content of the water being spread increases. Perhaps research will produce a soil conditioner that can attract settling particles and tend to add them to aggregates. Organic residues probably fall between grasses and soil conditioners in their ability to 'absorb' settling sediments. With present treatments it appears best to bypass water that exceeds a certain turbidity. A higher turbidity seems permissible for grasses than for organic residues and least for soil condttioners.

Good distribution of a soil conditioner at the light rate of application required is difficult, particularly in powder form. Distribution in powder form at optimum soil moisture becomes even more difficult on large areas. Perhaps application in solution form may be best.

Table 1--Infiltration rate for various treatments on small test ponds, Wasco, California

Vegetative treatment	Run	Year	Infiltration					
			Maximum		Minimum		Average	
			Rate	Elapsed time	Rate	Elapsed time	Rate	Elapsed time
			ft/day	day	ft/day	day	ft/day	day
Untreated and undisturbed	1[a]	1946	3.6	28	0.3	200	1.0	200
Cotton-gin trash	1	1948	2.8	2	0.3	30	1.0	30
	2	1948-49	6.2	48	1.3	247	3.2	247
	3	1950-51	7.3	32	1.4	594	3.5	594
	4	1951-52	12.6	25	2.6	227	5.8	227
Bermuda grass[b]	1	1946	2.7	26	0.4	112	1.7	112
	2	1946-47	3.8	11	1.5	252	1.8	252
	3	1947-48	11.1	25	0.5	270	3.5	270
	4	1948-49	7.1	29	0.6	294	2.1	294
	5	1951	6.9	48	1.8	89	3.6	89
	6	1952	11.6[c]	29	0.8	264	3.6	264
	7	1953	3.7	24	2.3	72	2.8	72
Soil conditioner Vama type[d]	1	1952-53	11.3	57	2.9	320	4.8	320
	2	1953-54	10.3	29	2.2	280	4.6	280
	3	1954	6.5	24	1.3	206	2.7	206
Soil conditioner[e]	1	1953	9.4	23	1.4	90	4.3	90
	2	1953-54	4.3	18	2.0	78	3.2	78
	3	1954	3.8	12	1.1	247	2.0	247

[a] All infiltration rates for subsequent untreated runs were reasonably similar to Run 1 when adquate drying occurred between runs.

[b] Sod laid and irrigated April 5, 1954; irrigated 4/24, 6/13, and 8/17, 1954.

[c] Adequate antecedent drying caused recurrence of approximate maximum rate of 1947-48 run.

[d] Calcium salt of vinyl acetate maleic acid.

[e] Ammonium lignin sulfonate and wood sugars.

Results of water and surface soil treatments on large areas

Vegetative treatments--Because of success on small ponds, cotton-gin trash and Bermuda grass were employed on basins of a few acres which are parts of large spreading grounds. The basins were formed by leveling land and building dikes. High infiltration rates on these basins could be expected if: (1) subsurface conditions do not limit the potential infiltration rate of the treatment, (2) serious compaction does not occur, and (3) there is no appreciable breakdown of structure. Infiltration rates on small test ponds are not reduced by the shallow hardpan or stratified layers as water may readily flow laterally over such layers. On a large spreading area, however, water is confined largely to vertical flow downward except near the boundaries. The rate of flow of water thus confined is reduced by any less pervious subsurface layers. The effect of such layers on reducing the infiltration rate increases as the size of the area increases. Location of the less pervious layer in the soil profile influences its effects also. Both compaction and breakdown of structure can be reduced if the soil is treated when it is quite dry, with a minimum of passes by the lightest practical equipment. It usually takes wetting and drying over a period of time for compaction to be relieved and destroyed structure to improve even with an assist from organic residues and grasses. Ripping may relieve compaction [DONEEN, HENDERSON, and FERRY, 1952].

Initial infiltration rates were low on basins with cotton-gin trash incorporated by discing, due to soil manipulation and compaction and the clogging of pores by the products of microbial decomposition (incubation). Prior to the 1954 spreading season the cotton-gin trash basins of the Poso spreading area were ripped to relieve compaction. During the 1954 season rates approached an average of 1.5 ft/day from an original low of about 0.3 ft/day. Greater increases in infiltration rate may be expected after complete decomposition of the cotton gin trash. However, it is the opinion of the writer that infiltration rates will not appreciably exceed 2.0 ft/day when surface-treated basins are operated as part of a large spreading area because of the influence of less pervious subsurface layers. This is discussed in more detail later.

At Minter Field, cotton-gin trash disced into a six-acre basin produced an average infiltration rate of 0.6 ft/day for the 1950 spreading season, as compared with an average rate of 0.8 ft/day for the untreated five-acre control. No spreading took place in 1951. Average infiltration rates increased to 0.7 and 0.9 on the cotton-gin trash basins and dropped to 0.5 and 0.7 on the control during the 1952 and early 1953 spreading seasons, respectively. During the late 1953 spreading period the average infiltration rate increased to 1.2 ft/day for cotton-gin trash with the control having an infiltration rate of 0.9 ft/day. The 1950 spreading season and to a lesser extent the 1952 and early 1953 seasons probably served as incubation runs for the cotton-gin trash. Changes in basin borders prevented comparisons in 1954.

Bermuda grass was planted on large basins in 1952 but results on well-established stands are yet to be obtained. Soil manipulation has probably produced detrimental effects that may be overcome by ripping or by wetting and drying over a period with an assist by the growing grass. An important advantage of grass is the possible economic return as a hay or forage crop. Bermuda grass will withstand severe droughts and partial submergence.

Soil-conditioner treatments--Infiltration rates averaged two feet per day on the first run on each of two one-half acre adjacent basins, one untreated and one treated with a soil conditioner of the Vama type. These rates occurred when surrounding basins of the Poso spreading area were operating at about 0.5 ft/day. Dikes for the one-half acre basins were constructed from the outside and tillage was limited to rototilling to prevent compaction and minimize structure breakdown. Presumably soil manipulation should be held to a minimum consistent with operations necessary, based on topographic features, water control, maintenance and other local conditions. A lateral flow opportunity was created for both the one-half acre basins when water was shut off from surrounding basins. Only the Vama-treated basin responded with an increase indicating a higher potential infiltration rate than the control. When water was limited to vertical flow beneath the Vama-treated basin, the infiltration rate was limited by a percolation rate of about two feet per day.

Subsurface borings revealed the top of a clay layer about 30 ft below the soil surface in the Poso spreading area. When continuity of flow exists between the soil surface and the clay layer, frequently associated with the rise of a perched water table, the percolation rates drop below two feet per day. However saturation is not required for continuity of flow to exist. DAY and LUTHIN [1953, 1954] point out that the conduction of water under tension may be fully as rapid as when positive pressures prevail and that under certain conditions capillary flow accounts for the entire seepage flux. The percolation rate of the clay layer mentioned is considerably below that of the relatively shallow stratified layers. It would appear that treatments to increase the infiltration rate beyond two feet per day are unwarranted. Costly treatments required to obtain infiltration rates of even two feet per day are questionable. The period of time a given amount of water is available and economic considerations are involved.

Infiltration rates were higher for the Vama-treated basins than for the untreated basins during the second run which took place in 1954. However, all rates were considerably lower than those observed during the first run. The turbidity of the water (higher than that used in small ponds) may have partially accounted for the clogging which took place.

Surface treatments based on soil profile and stratigraphy--If surface conditions limit the rate of flow and if the preparation of a spreading area reduces the infiltration rate below normal, treatments may hasten the recovery to normal and tend to exceed the normal. Soils whose permeability have been reduced by manipulation tend to revert back to normal in time due to such factors as wetting and drying, decomposition of natural organic matter, and the growth of native vegetation. The development of native cover, particularly if encouraged by spreading in semi-arid areas, may promote infiltration rates above normal.

If shallow less-pervious layers limit the rate of flow, then surface treatments to exceed the normal are not justified. Even though shallow layers may limit the flow initially, the surface may become the limiting condition as the spreading season progresses, CHRISTIANSEN and MAGISTAD [1945] and SCHIFF [1953]. In such cases, sufficient treatment to maintain an infiltration rate slightly above the percolation rate may be justified based on costs and conservation effected.

If less pervious layers are deep enough and if large quantities of water are available in a relatively short time, treatments that increase the infiltration rate may be warranted. Various combinations of conditions can exist that require local evaluation.

Subsurface soil treatments

Ripping--Ripping of shallow less-pervious layers has been tried in many areas to increase soil permeability under rainfall, irrigation, and spreading. In general, this method has been successful where less pervious layers contain little clay and where fines do not readily clog the large pores. Results are not yet available from the North Appalachian Experimental Watershed where a soil conditioner has been distributed in the soil by an attachment behind the ripper. Locally, ripping has been tried on soils with shallow hardpans and on stratified layers. Preliminary results range from little gain to doubling infiltration rates, particularly where initial rates were low due to compaction [CAMPBELL 1955]. Infiltration rates have not reached the 'satisfactory' 1.5 ft/day by this method alone. However, additional trials are planned and thought is being given to a companion treatment such as cotton-gin trash or soil conditioner to promote aggregation of loose soil.

Shafts--Gravel back-filled shafts four feet wide and 20 feet deep on Exeter sandy loam have been tested or prepared for future tests. Initial tests were made using surface sand filters over the 1 1/2-inch gravel. Shaft 37 drilled through soil of low permeability, contacted aquifer material representing 57 pct of the total interface of water and cylindrical shaft surface and bottom and gave a maximum injection rate of 1800 ft/day over the shaft area (12.6 sq ft). This is equivalent to 0.52 ac ft or 0.26 cfs. Approximately 13 ac ft of water moved through the shaft in 30 days and 26 ac ft were injected in 82 days. Shaft 36 contacting 31 pct aquifer material at the interface gave injection rates of about one-fifth those of Shaft 37.

The maximum injection rates obtained with Shaft 37 may be reasonably satisfactory although not yet evaluated economically. Research must develop methods to reduce clogging. The known sloughing of soil around the sides of the shaft undoubtedly retarded injection rates. High losses in hydraulic head across the interface of aquifers, determined by peizometer readings, gave further evidence of clogging.

A second run on Shaft 37 in 1954 produced injection rates about one-third those of the first run. There is little doubt that severe clogging was caused by the original sloughing. However, a contributing cause may have been microbial activity. It is doubtful whether there was sufficient drying of the interface between runs for recovery in injection rate. During the second run a pea-gravel mound was used in place of the sand filter. A surface crust developed on the mound, composed partially of algae, and apparently served effectively as a filter. Removal of the algae from part of the filter slightly increased the head and the injection rate.

Results indicate that: (1) shafts should be located by borings so that they contact sufficient aquifer material (a shaft so located and now operating at a high rate will be reported subsequently); (2) sloughing or dislodging fine material onto the interface of aquifers during digging or backfilling or injection water should be avoided; (3) pea gravel would probably give better support to the sides than larger gravel; (4) if feasible a shaft with sloping rather than vertical sides may reduce sloughing; and (5) a mound of pea gravel appears to make an adequate filter. Chlorination would undoubtedly reduce microbial activity. However, unless occasional treatments of chlorine are adequate such a procedure may be too expensive for normal spreading. Sufficient drying between runs may serve adequately or it may be cheaper to abandon shafts and construct new ones, particularly if they are shallow and relatively inexpensive. Chlorination tests are in progress on an untreated pond.

Results of injection tests based on approximately five months of operation by the Los Angeles County Flood Control District (1950) indicate that: (1) a pressure mound was established and could be maintained; (2) injection rates of between 0.5 and 2.3 cfs could be maintained in a well; (3) a constant injection rate could be maintained by the partial control of air entrainment, the prevention of the formation of bacterial slime, deposition of suspended solids and calcium carbonate, and adverse base-exchange reactions through chlorination of injection water (about 15 ppm) and exclusion of air; (4) an infiltration rate of 2 to 3 cfs per acre per day can be expected on sand dune deposits by chlorinating (about 3 ppm) to prevent growth of soil-clogging microorganisms; (5) injection rates of about 0.11 cfs can probably be maintained in pit-type 30-inch diameter gravel-filled wells penetrating into a shallow aquifer providing the water is first treated to prevent clogging.

Trenches and pits--The trench at Minter Field, ten feet wide at the bottom, 1000 ft long, and ten feet deep with 3 to 1 side slopes contacts aquifers along a portion of the bottom and sides. In a 12-day period early in January 1954, 81.4 ac ft were supplied to the ditch, equivalent to a rate of 2 1/2 ft/day based on a water surface area of 2.16 acres. A second run of about 60 days April-May, 1954 resulted in an average injection rate of about 1.5 ft/day.

Injection rates of both the first and second run were lower than expected and were due largely to the movement of loose, small particles of soil lying on the surface after construction. Infiltration rates based on infiltrometers were three times higher on Vama-treated strips of the trench than on untreated portions. A piezometer located in the center of the trench and nine inches beneath the surface showed an initial head loss of 2.7 ft which increased to eight feet out of a possible 10.7 ft at the end of the 55-day first run. Deeper piezometers showed a rising perched water table, however this table did not rise high enough during the run to interfere with the injection rate of the ditch. On the surface of the ditch a pronounced crust of fine textured material formed which subsequently cracked and curled upon drying. Fine-textured material was found in layers between sand layers down to about four or five inches.

Recent infiltrometer runs were made on the clogged surface, on the sand with the clogged surface removed, and on the clogged surface with Vama incorporated. Infiltration rates were high and similar on the sand and Vama-treated surface and about twice that of the clogged surface. Based on all observations, it appears that the bottom of the ditch and the sides for a short distance above the bottom should be scraped down to sand. The grade established should slope up from the inlet or at least be level so that when water is brought in slowly little erosion will occur. Application of a soil conditioner over most of the scraped area to aggregate loose soil particles and promote aggregation where aquifer material is not present seems desirable. A small portion of the bottom will be treated with another type of soil conditioner and another portion with organic matter and tested with infiltrometers. It is believed that organic matter will withstand some settling of material in the injection water better than soil conditioners. A top layer of pea gravel on the trench is being considered in view of the high infiltration rates obtained with such a layer on the Peoria infiltration pit.

At the Poso spreading area a ten-foot pit (similar in action to a trench) with a water surface area of 1.5 ac, bottoming in an open coarse sand, took water at a maximum of six and an average rate of about five feet per day for 23 days, starting January 29, 1954, [CAMPBELL, 1955]. After this time the perched water table rose to contact the saturated column below the ditch and injection rates declined rapidly to near zero. Piezometers indicate this perched water table rests on the clay layer which is about 30 ft below the soil surface. The barrier at Minter Field apparently is farther below the soil surface and seems to lack the continuity of the one at Poso.

Infiltration and lateral flow interpreted by the Darcy Equation--The Darcy Equation for the velocity of flow, v, may be written

$$v = k\,(h_s + y)/y \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

where k is the proportionality constant (frequently called the coefficient of permeability), h_s is the surface head and y is the length of saturated soil column. By definition the infiltration rate f equals v. When y is small, h_s may constitute most of the hydraulic head and f increases almost directly proportional to increases in h_s [SCHIFF, 1953]. When y is large $(h_s + y)/y$ approaches unity and small variations in h_s have little affect on f. Generally soil conditions are such that y is small and the use of reasonable high heads will increase the infiltration rates. ROBINSON and ROHWER [1955] show that the seepage rates in canals are proportional to the surface head plus some distance below the surface.

Since v and f are computed for the total area and the water moves through the pore space, k includes porosity. It has been shown by FAIR and HATCH [1933] and others that

$$k = (1/c)\,[g d^2 (r/u)\, F(\alpha)] \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

where c is a numerical coefficient, g is the acceleration of gravity, d is a particle parameter, r is the density, u is the viscosity, and $F(\alpha)$ is a porosity factor that has been equated to

$(1 - \alpha)^2/\alpha^3$, where α is the ratio of voids to the volume. This break-down of k leads to a better understanding of the factors involved and adds to the information available for analysis. The particle parameter is dependent on the size, shape, and arrangement of soil particles and is a challenging field problem in classification and evaluation.

BODMAN and COLMAN [1943] and others have presented laboratory work helpful to an understanding of soil-water movements. Development of (3) to (5), below, is based on the theoretical aspects of water spreading by HALL [1955]. The area a_1 occupied by a mound developing on a less pervious subsurface layer beneath an area a on which water is spread is of interest in design. The velocity of flow v_1 through the less pervious subsurface layer of permeability k_1 is

$$v_1 = k_1 (h_w + y_1)/y_1 \quad \ldots\ldots\ldots\ldots \quad (3)$$

where h_w is the depth of water on the less pervious layer and y_1 is the length of saturated column beneath the surface of this layer. From (3) it may be seen that v_1 increases as h_w builds up on a less pervious subsurface layer. The actual percolation rate through such layers also depends upon the permeability and length of saturated column.

Multiplying (1) and (2) by areas a and a_1, respectively, gives the quantities of water Q and Q_1 flowing through these areas respectively. When the length of saturated column y is sensibly constant, and all of the water infiltrating through the spreading area a moves through a_1, Q may be equated to Q_1 and

$$a_1 = Q/[k_1 (h_w + y_1)/y_1] \quad \ldots\ldots\ldots\ldots \quad (4)$$

The average hydraulic gradients are involved in the expressions, primarily since h_w will vary and will also affect the length y_1. As $(h_w + y_1)/y_1$ in (4) approaches unity, a_1 approaches a maximum

$$a_1 = Q/k_1 \quad \ldots\ldots\ldots\ldots \quad (5)$$

Where relatively shallow less-pervious layers exist, such as at Poso where piezometers indicate a less pervious layer at 30 ft, it may be desirable to spread water on only portions of the area based on an infiltration rate - percolation rate ratio [SCHIFF, 1954]. This idea is also supported by (5) which shows that the area occupied by lateral flow over a subsurface layer varies directly with the permeability of the layer. Portions of the area not used for spreading may be farmed or used in a rotational system of spreading. Such a system may permit as much or possibly more water to infiltrate.

Tools to determine the suitability of a potential spreading area--Coarse-textured soils with no subsurface layers of low permeability either overlying the basin to be recharged or hydraulically upslope are good conditions for spreading. Frequently only a soil inspection in the vicinity is necessary to determine if such sites exist. If well logs are not sufficient, cable tool test holes are helpful to determine the stratigraphy. Where feasible jetting is rapid and a relatively economical method of determining stratigraphy [REGER, PILLSBURY, REEVE, and PETERSEN, 1950; DONNAN and BRADSHAW, 1952]. Influencing geologic conditions should be known.

A soil survey and laboratory analysis to obtain information on such factors as texture, aggregation, organic matter, and chemical conditions are desired, particularly where fine- to medium-textured soils exist. Information is also needed on the quality of the water to be spread as well as its turbidity at various times. Knowledge is developing on factors that affect permeability and the hydraulic gradient. An important tool is the infiltrometer. Infiltrometers used by the writer are of various lengths and vary in size from nine-inch cylindrical metal tubes to square infiltrometers with an area of 43.6 sq ft. An infiltrometer extending nine inches into the soil and a deep infiltrometer extending into hardpan at Minter Field gave infiltration rates of about eight and 0.6 ft/day, respectively. The rate of 0.6 ft/day was reasonably close to basin performance in the area at the time. The action of an infiltrometer involves the surface head used, the depth of the infiltrometer in soil and the soil properties; a pool of water or buffer surrounding an infiltrometer affects the infiltration rate [SCHIFF, 1953]. Under prolonged submergence a buffer helps confine water to vertical flow downward beneath the infiltrometer, particularly if hydraulic head exists at the base of the infiltrometer. Much of the flow on a large area is vertically downward. A 'balanced buffer' or a depth of water in the buffer equal to that in the infiltrometer is desirable.

Applying tools to determine feasibility of water spreading--Infiltrometers were used to determine both infiltration rate curves for watersheds and for potential water-spreading areas in the Tehachapi area, California. Water was applied in drop form to simulate rainfall on watersheds and a constant head was used in infiltrometers on potential spreading areas. The infiltration rate curves were used to develop runoff from individual watersheds based on overall runoff methods suggested by TROXELL [1948] and developed for the area by DONNAN and LITZ [1953]. This report also presented information on consumptive use based on methods by BLANEY and CRIDDLE [1950]. Rates of runoff were determined based on a method developed by SCHIFF [1951]. In Sand Canyon it was found that the average annual runoff was equal to the consumptive use of crops on the valley floor below. Infiltrometers indicated a satisfactory site at the mouth of the canyon and a spreading area was constructed. This spreading area may be the forerunner of others in the valley.

Infiltrometer runs should be of sufficient duration, one or more months, for the infiltration curve to reach the characteristic leveling-out associated with prolonged submergence in water spreading. Initial fluctuations and often times the early decline are misleading. On the proposed El Rio Spreading Ground in Ventura County, California, a 0.001 acre infiltrometer, surrounded by a buffer, was driven through the fine sandy loam into the sand below, without disturbing the topsoil within the infiltrometer [SCHIFF, 1954]. The soil within the infiltrometer immediately adjacent to the sides was tamped to insure a good bond between soil and metal and thus prevent leakage. The buffer was used to confine water to vertical movement downward by preventing lateral flow, simulating the action of much of a large spreading area. This was a precautionary measure, since the sides of the infiltrometer extended into sand of much higher permeability than the soil above. Also, for the depth of water in the infiltrometer and length of saturated column, little hydraulic head would be expected at the base of the infiltrometer in sand. No water stood in small metal tubes or piezometers adjacent to the inner side of the infiltrometer one-half inch from the bottom. Positive pressure would have had to exist for appreciable lateral flow to occur away from the infiltrometer. Lateral flow due to capillary forces ceases early in a prolonged run, as field capacity is reached in a short time. A buffer to prevent lateral flow due to this cause is generally unnecessary for the prolonged runs required.

Other infiltrometers used in the El Rio area were equipped with piezometers on the outside and soldered to the infiltrometers one-half inch above the bottom end. In all cases infiltrometers of sufficient length were used to extend through the fine- and medium-textured soils into sand. Positive pressures did not exist in the piezometers for the head used. A good check was afforded by comparing infiltration rates obtained with infiltrometers installed on the nearby Saticoy spreading ground against actual infiltration rates obtained on some of the operating basins. Infiltrometers already described were installed on basins not in operation and a falling-head type was used on operating basins. Infiltration rates obtained were in good agreement. Infiltration rates obtained on the proposed El Rio spreading ground were logical for the different soils tested in relation to the soils at Saticoy spreading ground.

Although a few well logs within and adjacent to the proposed El Rio area indicated a good subsurface condition for rapid utilization of pore space above the ground-water table, it was thought best to support these with a few cable-tool test holes. The general inspection and survey of the area, the infiltrometer work, well logs and cable-tool test holes all indicated the suitability of the proposed area. Water will be diverted from the Santa Clara River to supply the El Rio spreading ground now being constructed by the United Water Conservation District.

Conclusions

Field investigations and laboratory experiments are producing information directed toward interpreting the physical, chemical, and biological influences of soil and water properties on infiltration. Additional tools, such as soil surveys, infiltrometers, well logs, jetting and cable-tool test hole rigs are available to characterize the feasibility of an area for water spreading. Utilizing these tools, sites have been selected for water spreading. If sites with porous soils do not exist, vegetative, chemical, soil-conditioner, and mechanical treatments are being developed as are operational procedures to increase the infiltration rate. If subsurface conditions limit flow, as in the San Joaquin Valley, surface-soil treatments may be limited or unwarranted. Research is producing information on injection methods, such as shafts, trenches and wells, which cut through less-pervious soil layers. Economical methods are sought to prevent soil clogging.

Research must be directed toward the development of operational procedures to successfully apply treatments, originating from the laboratory and small test ponds, to large areas. Where subsurface conditions limit flow, portions or strips rather than the entire area may possibly be used for spreading. This method visualizes a 'subsurface lake' forming on the less-pervious subsurface soil layer. Strips may be spaced on an infiltration rate - percolation rate ratio. It may be desirable to increase this ratio by surface - treatment of strips. It is conceivable that strips may take the form of trenches or that shafts may be used to inject water that would also move laterally. More water might infiltrate in the treated-strip method than if the entire area is flooded. Such a method might permit farming or other land use between strips and warrants further investigation. A rotational system, where some portions of the area are flooded while some are dried, needs more investigation. Portions would be flooded only while infiltration rates are high. Thus portions would be dried more frequently for recovery in infiltration rate associated with released gas and the drying of the by-products of decomposition.

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STUDY OF RAINFALL STATION LOCATIONS IN SOUTH CHICKAMAUGA CREEK WATERSHED

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Abstract--A 428-sq mi watershed was studied for the purpose of determining the number and location of reporting rainfall stations needed to provide the desired accuracy of average watershed rainfall for stream-flow prediction purposes. Data on storms occurring during a 12-month period are analyzed and a chart presented which shows the probable difference from average watershed rainfall to be expected for winter storms when various numbers of best and random stations are used to estimate rainfall.

Introduction--The study of rainfall station locations in South Chickamauga Creek watershed was made to provide information on the number and proper location of reporting stations needed to provide the desired accuracy of average watershed rainfall for stream-flow prediction purposes. The South Chickamauga Creek watershed has a drainage area of 428 sq mi above the United States Geological Survey stream gage near Chickamauga (see Fig. 1) and is located southeast of Chattanooga, Tennessee. The watershed is approximately a 20-mile square with the addition of McLemore Cove extending about 15 mi to the southwest. The valley floor varies from elevation 900 to elevation 650 sloping down from the southeast to the northwest. Topography to the north continues the general slope of the valley floor. Lookout Mountain ridge, rising to elevation 2200, lies to the west of the watershed, and a plateau on the south is only a little lower. Several ridges paralleling Lookout Mountain and rising to elevations of 1000 to 1500 ft lie within and east of the watershed.

A rainfall station network (see Fig. 1) was established consisting of 18 stations within the watershed and eight stations adjacent to the watershed. Fourteen of the interior stations were located to provide fairly uniform coverage of the watershed and four stations were added to provide data on the effect of topography. Nonrecording gages were used except at three locations where recording gages were necessary because observers were not available. Daily telephone reports were received from stations 90 (Chickamauga Dam), 488 (Chattanooga Airport), 566(Chickamauga Park), 721 (Ringgold), and 722 (Kensington). All stations reported semi-monthly by mail. Nonrecording gages within the watershed were observed each morning, and recording gages recorded rainfall continuously from December 1, 1952, through November 30, 1953. Records were good except at Station N which was replaced in June by Station Na about three miles to the south.

This study was based on rainfall by storm periods, because runoff from individual storms is needed for making stream-flow predictions. In order to exclude storms which were unimportant for this purpose, the following criteria were used to select storms for study: (1) December 1952 through June 1953, storms which exceeded 0.5-inch at any station; (2) July through November 1953, storms which exceeded 1.0-inch at any station, or which exceeded 0.5-inch average for the watershed. The 22 winter storms which occurred before April 30, 1953, had fairly uniform distribution. This is typical for this season and these storms are the most important for stream-flow prediction purposes. The 21 summer storms, which occurred after April 30, 1953, were largely of the convectional type with numerous high and low spots. Data on these storms are shown in Table 1. The arithmetic mean of the 18 watershed stations, and the weighted-area watershed mean, for each storm are shown in this table. The weighted-area watershed mean by the Thiessen method is used as the best estimate of watershed mean rainfall in this study.

Analysis of data--Data for these 22 winter storms were analyzed to determine the individual station providing the closest estimate for the watershed mean rainfall by storms. The best groups of two, three, and four stations were also determined. The method followed was to compute for a selected station or group of stations the difference from the watershed mean rainfall for each storm. These storm differences were then analyzed by statistical methods to determine for that station or group of stations (1) the average storm difference $\bar{d}$, (2) the range of storm differences, (3) the standard deviation from the average storm difference s, and (4) the probable range of storm differences $\bar{d} \pm 2.271s$ (Tolerance interval = $\bar{d} \pm 2.271s$ for sample size 22, confidence limit 95 pct, tolerance

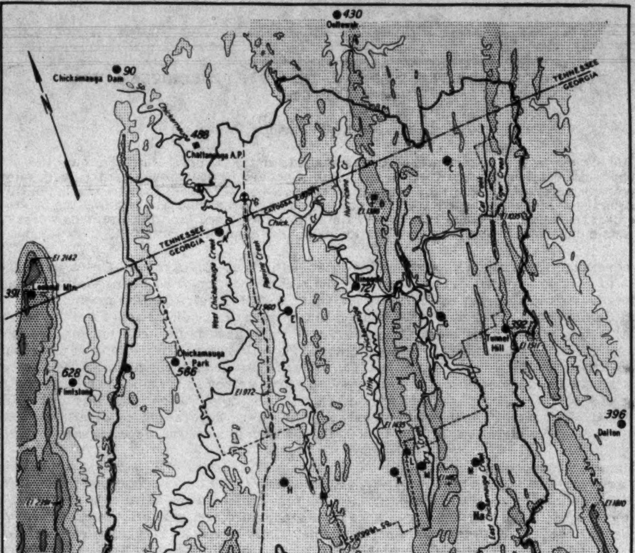

430
Ooltewah
90
Chickamauga Dam
488
Chattanooga A.P.
TENNESSEE
GEORGIA
391
Lookout Mtn.
628
Flintstone
Chickamauga Park
586
721
Ringgold
392
Tunnel Hill
396
Dalton
722
Kensington
Lafayette
82
West Chickamauga Creek
699
Rising Fawn
LEGEND
ELEVATION 2000 AND ABOVE
ELEVATION 1500 TO 2000
ELEVATION 1000 TO 1500
ELEVATION 800 TO 1000
ELEVATION 650 TO 800
STREAM GAGING STATION
RAINFALL STATION — NON-RECORDER
RAINFALL STATION — RECORDER

Fig. 1--South Chickamauga Creek watershed rainfall stations

limit 75 pct. [DIXON and MASSEY, Introduction to statistical analysis, McGraw-Hill, 1951, p. 110].)

Storm differences for the 21 summer storms were also analyzed for the same stations and groups of stations as were analyzed for winter storms. Best station combinations for summer storms were not determined because of the characteristic spotty distribution and the small amount of runoff which develops. The results of these analyses are shown on Table 2. The station combinations in Table 2 were selected for winter storm results. The analysis of summer storm differences is given for the same station combinations without regard to accuracy.

Individual stations--These analyses show little difference in the relative accuracy of Stations M and 566 for determining average watershed rainfall from an individual station. The average storm difference for Station M is -0.031 and the probable range is -0.38 to +0.32. For Station 566 the average difference -0.068 is larger while the probable range -0.40 to +0.27 is smaller. Slightly larger differences can be expected for winter storms from Stations P, B, and E. Stations A and Q, located near the extreme north and south edges of the watershed, are the worst individual stations for winter storms.

For the 21 summer storms, Station B, located on a ridge, is the best individual station which was analyzed. The probable ranges of differences for Stations M, 566, and E are slightly larger, and Stations A and Q fall in about the same range as these stations.

Note the marked difference between winter storms and summer storms at Station Q and at the adjacent valley Station P. At Station Q the average winter storm difference is +0.242-inch and the average summer storm difference is +0.025-inch; while at Station P these differences are +0.023-inch and +0.167-inch, respectively. This appears to occur rather generally at stations located at high elevations and at stations located in well-defined valleys.

When differences for winter storms at all stations except D, 392, and Q are grouped together, the resulting average difference is 0.0-inch, range -0.64-inch to +1.07-inch, and standard deviation 0.233-inch. This analysis indicates that if reports are obtained from any one of the 15 stations, the probable range of storm differences, as previously defined, will be -0.53-inch to +0.53-inch.

Two-station combinations--The arithmetic mean of winter storm rainfall at Stations E and L gives the best results of two-station combinations. The average storm difference is -0.014 and the probable range is -0.17 to +0.14. These values are less than half the corresponding values for the best individual station. Stations E and J give only slightly poorer results. The best pair of reporting stations, Stations 721 and 722, has about the same average storm difference as Stations E and L, but a probable range nearly twice as large.

For the 21 summer storms Stations E and L and also Stations E and J give little improvement over the individual stations. The probable range of differences for reporting Stations 721 and 722 is smaller than for either of these two pairs of stations. It will be noted that both Stations L and J are located on ridges.

When differences for winter storms for all two-station combinations which give reasonable areal cover are grouped together, the resulting average difference is +0.001-inch, range -0.55 to 0.73-inch, and standard deviation 0.141-inch, with a probable range ±0.32-inch.

Three-station combinations--The arithmetic mean of winter storm rainfall at Stations 566, 721, and L gives the best results of three-station combinations. The average storm difference is -0.015 and the probable range is -0.14 to +0.11. The results for three additional combinations are almost as good. The three reporting stations (566, 721, and 722) give materially larger average storm difference and probable range than the above groups of stations.

For the 21 summer storms these groups of stations show a material improvement in probable range over two-station combinations which were analyzed, although the average storm differences are larger. The three watershed reporting stations give about as good results as the other combinations.

Random three-station combinations for winter storms give average difference -0.006-inch, range -0.45-inch to 0.42-inch, standard deviation 0.101-inch, and probable range -0.24-inch to +0.22-inch.

Four-station combinations--The arithmetic mean of winter storm rainfall at Stations 566, 721, L, and P gives the best results of four-station combinations. The average storm difference is -0.006

Table 1--Rainfall in inches for selected storms,

Storm No.	Storm Date	SCA	SCB	SCC	SCD	566	SCE	721	SCG	392	SCH	SCJ	SCK	SCL
	December 1952 - April 1953													
	1952													
1	Dec. 2	0.61	0.63	0.65	0.49	0.58	0.63	0.66	0.62	0.65	0.70	0.75	0.70	0.70
2	Dec. 5	1.37	1.03	0.90	1.30	1.17	1.19	1.10	0.93	0.88	1.16	0.93	0.91	0.90
3	Dec. 9 -10	1.00	1.14	1.39	0.68	1.07	1.01	1.15	1.83	1.52	1.20	1.42	1.54	1.60
4	Dec. 30	1.43	1.34	1.54	1.63	1.53	1.57	1.54	1.64	1.66	1.69	1.82	1.68	1.68
	1953													
5	Jan. 2	0.52	0.40	0.48	0.50	0.48	0.37	0.39	0.38	0.37	0.51	0.43	0.44	0.32
6	Jan. 7 -10	2.68	2.60	2.50	2.87	2.74	2.77	2.85	3.07	2.92	3.66	3.71	3.63	3.44
7	Jan. 17	0.56	0.30	0.39	0.51	0.51	0.40	0.26	0.42	0.35	0.30	0.34	0.35	0.32
8	Jan. 20	0.13	0.48	0.44	0.17	0.18	0.50	0.54	1.13	0.83	0.61	0.76	1.11	1.07
9	Jan. 23	1.01	0.94	0.75	1.06	0.95	0.84	0.95	0.79	1.15	0.95	0.86	1.06	0.93
10	Jan. 28	0.29	0.33	0.37	0.39	0.34	0.27	0.26	0.42	0.30	0.22	0.25	0.41	0.36
11	Feb.6 -7	0.66	0.80	0.74	0.81	0.73	0.75	0.77	0.70	0.80	0.68	0.68	0.65	0.71
12	Feb. 10-12	1.80	1.81	1.91	1.98	1.97	1.89	1.96	1.89	2.49	1.88	1.88	2.04	1.86
13	Feb. 15-16	0.74	1.29	1.50	1.24	1.31	0.65	0.74	1.40	1.70	0.58	1.59	0.76	1.46
14	Feb. 19-21	3.95	2.86	2.94	2.91	2.63	3.21	3.90	2.31	2.58	2.90	2.82	2.55	2.42
15	Feb. 24-25	0.27	0.25	0.24	0.33	0.33	0.35	0.37	0.38	0.33	0.41	0.34	0.38	0.46
16	Mar. 2 -3	1.22	0.95	0.94	0.99	1.01	1.12	1.19	1.25	0.90	1.15	1.42	1.22	1.08
17	Mar. 4	1.19	1.14	1.16	1.20	1.22	1.18	0.90	1.22	1.00	1.02	1.28	0.93	0.80
18	Mar. 11-12	0.44	0.40	0.70	0.33	0.42	0.37	0.46	0.59	0.50	0.78	0.43	0.49	0.51
19	Mar. 21-24	0.95	0.64	0.94	0.61	0.76	0.84	0.70	0.59	0.63	1.01	0.89	0.82	0.84
20	Apr. 10	0.39	0.52	0.38	0.11	0.07	0.06	0.06	0.04	0.10	0.37	0.52	0.66	0.56
21	Apr. 12	1.20	1.24	1.46	1.13	1.18	1.24	1.42	1.19	1.13	1.09	1.05	1.19	1.24
22	Apr. 30	1.89	2.15	2.21	1.64	1.76	1.99	2.14	1.98	2.10	1.30	1.81	1.97	1.80
Sum		24.30	23.24	24.53	22.88	22.94	23.20	24.31	24.77	24.89	24.17	25.98	25.49	25.06
Mean		1.10	1.06	1.11	1.04	1.04	1.05	1.10	1.13	1.13	1.10	1.18	1.16	1.14
	May - November 1953													
	1953													
23	May 2	0.64	0.44	0.21	0.26	0.28	0.15	0.15	0.21	0.18	0.46	0.27	0.24	0.29
24	May 3 -7	2.46	1.53	2.21	2.44	2.24	1.51	1.37	2.04	2.16	1.50	1.69	1.94	2.01
25	May 14-15	0.49	0.45	0.39	0.59	0.58	0.58	0.40	0.21	0.28	0.47	0.27	T	0.20
26	May 18-19	1.02	1.02	1.44	0.86	1.12	1.06	1.56	1.24	2.15	1.57	1.41	2.05	1.83
27	Jun. 10	0.34	0.57	0.64	0.03	0.08	0.18	0.55	0.42	0.30	0.01	0.12	0	0.08
28	Jun. 16	0.96	1.20	0.73	1.00	0.90	1.05	1.60	1.30[a]	0.97	1.37	1.42	1.66	1.22
29	Jun. 21-22	0.75	0.70	0.68	0.99	0.67	0.87	1.55	1.25[a]	0.87	0.47	0.45	0.73	1.29
30	Jun. 26	0	0	0	0.60	0.02	0	T	0	0.08	0.08	0.20	0.66	0.45
31	Jun. 27	0.24	0.18	0.04	0.61[a]	0.65	0.24	0.17	. . .	0.28	0.27	0.13	0.73	0.67
32	Jul. 3	0.34[a]	0.80	1.09	0.19	0.15	0.43	0.51	0.74	0	0.85	0.30	0	0.07
33	Jul. 7 -8	2.00	1.25	0.84	1.00	0.99	2.81	1.34	1.39	0.93	1.20[a]	2.57	1.78	1.95
34	Jul. 15-16	0.78	0.74[a]	0.56	1.08	0.85	1.09	0.74	0.62	0.56	0.49	0.90	0.90[a]	0.61
35	Jul. 17-18	2.69	2.30	1.78	2.08	1.47	2.31	2.20	2.50	2.68	1.98	2.86	2.70[a]	1.81
36	Jul. 20	0	0.21[a]	0.42	0	0	0	0	0	0	0	0	0	0.04
37	Jul. 21-22	2.98	2.57[a]	2.01	2.67	1.95	1.71	1.70	2.60	2.60	2.51	2.40	2.68	2.23
38	Aug. 1 -2	0	0.30	0.62	0.06	0.12	0.10	0.16	1.13	1.60	0.57	0.48	0.40[a]	0.18
39	Aug. 7 -8	1.59	0.90	1.03	0.39	0.44	0.42	0.55	0.36	0.30	0.99	0.71	0.83	0.54
40	Sep. 4 -5	0.33	0.58	0.77	0.95	0.62	0.86	0.60	1.42	1.72	0.95	1.23	1.34	1.52
41	Sep. 19	1.16	1.11	1.08	1.18	1.18	1.32	1.20	1.13	1.24	1.16	1.15	1.14	1.02
42	Sep. 24-26	0.77	0.75	1.34	1.06	1.07	0.90	0.91	0.96	0.90	1.05	1.01	1.06	1.00
43	Nov. 22	0.61	0.56	0.62	0.73	0.60	0.62	0.35	0.52	1.33	1.36	0.45	0.31	0.37
Sum		20.15[a]	18.16[a]	18.50	18.77[a]	15.98	18.21	17.61	. . .	21.13	19.31[a]	20.02	21.15[a]	19.38
Mean		0.96[a]	0.86[a]	0.88	0.89[a]	0.76	0.87	0.84	. . .	1.01	0.92[a]	0.95	1.01[a]	0.92

[a] Interpolated or partly interpolated [b] Station SCNa after June 30, 1953 . . . No report or incomplet

South Chickamauga Creek watershed

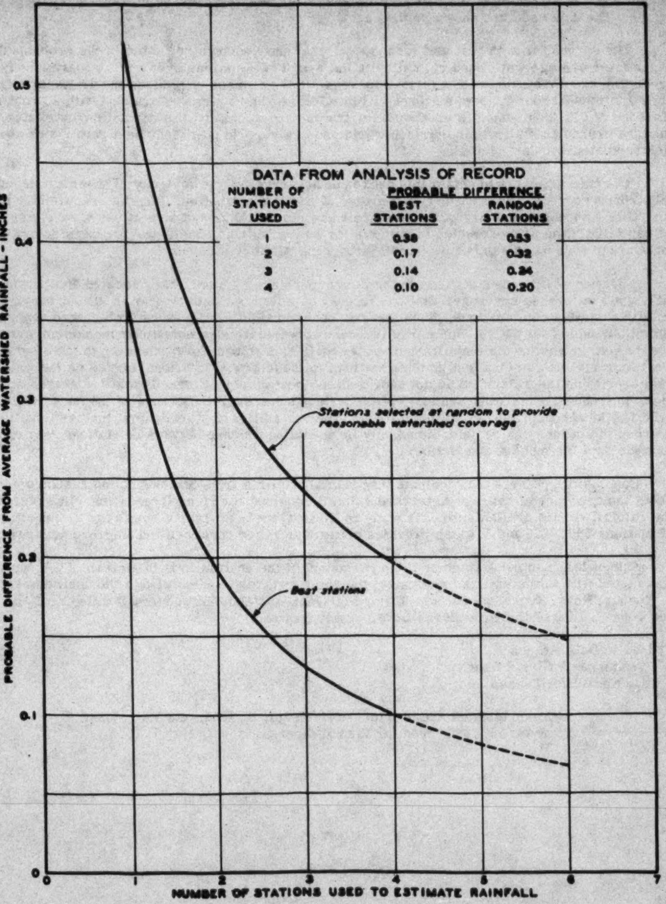
					Sum	Arithmetic mean	Adjacent stations							Weighted ar watershed m
SCM	SCN[b]	722	SCP	SCQ			430	488	391	628	396	82	669	
						December 1952 - April 1953								
0.60	0.70	0.79	0.83	0.88	12.17	0.68	0.52	0.54	0.57	0.56	0.78	0.65	0.74	0.68
0.68	0.75	1.06	1.19	1.51	18.96	1.05	1.20	1.22	1.81	1.59	. . .	0.90	1.39	1.07
1.60	1.60	1.55	1.32	1.34	23.96	1.33	1.18	0.94	0.73	0.42	2.01	1.60	1.18	1.32
1.30	1.80	1.73	1.93	1.93	29.44	1.64	1.60	1.46	1.46	1.46	. . .	1.65[a]	1.55	1.64[a]
0.41	0.70	0.50	0.46	0.60	8.26	0.46	0.40	0.52	0.53	0.44	1.56	. . .	0.41	0.47
3.05	3.75	2.92	3.33	3.80	56.29	3.13	2.88	2.43	2.78	2.86	3.08	. . .	3.80	3.09
0.34	0.35[a]	0.40	0.48	0.44	7.02[a]	0.39[a]	0.30	0.51	0.53	0.48	. . .	0.25	0.49	0.40[a]
0.63	0.45	0.38	0.51	0.99	10.91	0.61	0.30	0.12	0.16	0.10	. . .	0.65	0.20	0.54
0.98	0.70	1.22	1.23	1.28	17.65	0.98	0.96	0.87	1.15	1.08	1.01	. . .	0.89	0.98
0.41	0.35	0.34	0.39	0.51	6.21	0.34	0.23	0.25	0.25	0.37	0.40	0.20	0.28	0.33
0.70	0.54	0.77	0.80	0.80	13.09	0.73	0.70	0.72	0.76	0.74	0.24	. . .	0.67	0.72
1.91	1.90	2.02	1.57	1.76	34.52	1.92	2.22	2.28	2.43	2.01	1.50	1.55	2.15	1.90
0.98	1.63	0.53	0.87	1.38	20.35	1.13	1.42	1.22	0.89	1.19	1.66	1.25	1.09	1.08
2.82	2.99	2.36	2.49	3.48	52.12	2.90	3.05	2.69	2.90	3.02	2.80	3.30	2.37	2.88
0.43	0.34	0.48	0.49	0.51	6.69	0.37	0.20	0.33	0.42	0.30	0.33	0.25	0.50	0.37
1.12	0.94	1.32	1.17	1.55	20.54	1.14	1.02	1.10	0.81	0.97	1.13	1.00	0.97	1.13
0.85	0.47	1.08	1.26	1.06	18.96	1.05	1.20	1.08	1.17	1.18	0.89	0.75	0.98	1.07
0.54	0.47	0.38	0.38	0.40	8.59	0.48	0.39	0.41	0.30	0.43	0.38	. . .	0.33	0.48
0.83	0.61	1.13	1.02	1.69	15.50	0.86	0.89	0.81	1.12	0.80	0.63	1.15	0.78	0.88
0.55	0.55	0.30	0.16	0.08	5.48	0.30	0.10	0.26	0.22	0.19	. . .	0.60	0.45	0.31
1.07	1.43	1.01	1.23	1.23	21.37	1.21	1.39	1.39	1.28	1.20	. . .	0.90	1.24	1.21
1.95	1.83	1.65	1.83	2.55	34.55	1.92	2.10	2.39	2.61	1.60	2.25	1.85	20.2	1.89
23.75	24.85[a]	23.92	24.94	29.77	. . .	24.62	24.25	23.54	24.88	22.99	25.50[a]	. . .	24.48	24.44
1.08	1.13[a]	1.09	1.13	1.35	. . .	1.12	1.10	1.07	1.13	1.04	1.16[a]	. . .	1.11	1.11
						May - November 1953								
0.25	0.32	0.42	0.46	0	5.23	0.29	1.10	0.70	1.22	0.55	0.68	0.30	0.13	0.34
1.84	0.77	3.26	3.21	2.49	36.67	2.04	1.99	1.65	2.41	2.15	2.66	2.10	3.15	2.08
0.26	0.21	0.60	0.60	0.47	7.05	0.39	0.42	0.64	0.53	0.32	0.15	0.35	0.83	0.43
2.47	2.66	1.33	1.34	1.57	27.70	1.54	1.38	1.39	2.13	0.85	3.11	1.15	1.16	1.47
0.08	0.20	0	T	0.24	3.84	0.21	0.35	0.13	0.14	0.12	0	0	0.05	0.21
1.11	. . .	1.90	2.02	1.62	22.03[a]	1.30[a]	1.02	0.83	1.00	1.47	1.23	. . .	1.72	1.30[a]
1.01	. . .	0.20	0.16	0.06	12.70[a]	0.75[a]	0.86	0.72	1.13	1.73	0.52	. . .	0.19	0.70[a]
0.50	. . .	0.08	0.76	0.04	3.47	0.20	0	0	0.02	0.25	0.08	0.15	0.13	0.19
0.22	. . .	0.06	0.11	0.23	5.23[a]	0.31[a]	0.05	0.25	0.22	0.27	0.30	0	0.14	0.27[a]
0	0.25	0	0.01	0.04	5.77[a]	0.32[a]	0.02	0.26	0.16	0.35	T	0	0.04	0.35[a]
1.21	1.64	1.24	1.82	0.92	26.88[a]	1.49[a]	1.26	1.56	1.73	1.02	1.17	1.45[a]	2.00	1.50[a]
1.40	0.43	0.96	2.31	1.65	16.67[a]	0.93[a]	1.08	0.72	1.61	0.52	0.46	0.90	1.30	0.90[a]
2.05	2.92	1.58	1.80	2.46	40.17[a]	2.23[a]	2.17	2.37	1.86	1.90	1.54	0.74	1.46	2.18[a]
T	0	0.45	1.04	0.85	3.01[a]	0.17[a]	0	0	0	0	0.07	0	0.09	0.20[a]
2.60	2.09	1.66	2.18	1.56	40.70[a]	2.26[a]	1.22	2.10	2.91	2.77	3.50	2.00	2.19	2.22[a]
0.18	0	0	0	0.35	6.25[a]	0.35[a]	1.42	0.23	0	0	0	. . .	0.27	0.32[a]
T	1.36	1.05	1.13	0.24	12.83	0.71	1.15	1.51	0.71	0.34	0.62	. . .	0.98	0.85
1.00[a]	0.35	0.76	0.57	0.72	16.29[a]	0.90	0.40	0.59	0.52	0.33	1.21	0.75	0.45	0.82[a]
1.00[a]	1.55	0.95	1.24	1.64	21.45[a]	1.19[a]	1.40	1.15	1.48	1.36	1.15	1.25	1.20	1.18[a]
1.60	1.67	1.51	1.55	1.65	20.76	1.15	0.62	0.99	0.90	1.04	1.31	1.25[a]	0.64	1.16[a]
0.61	1.23	0.81	0.60	1.13	12.81	0.71	0.45	0.50	0.74	0.88	1.24	0.90	0.77	0.74
19.79[a]	. . .	18.82	22.91	19.93	. . .	19.44	18.36	18.29	21.42	18.22	21.00	. . .	18.89	19.41
0.94[a]	. . .	0.90	1.09	0.95	. . .	0.93	0.87	0.87	1.02	0.87	1.00	. . .	0.90	0.92

Table 2--Summary of storm differences from watershed mean for selected station combinations, South Chickamauga Creek watershed

Stations	December - April storms					May - November storms				
	Total rainfall 22 storms	Observed storm differences			Probable range $\bar{d} \pm 2.271s$	Total rainfall 21 storms	Observed storm differences			Probable range $\bar{d} \pm 2.271s$
		Average $\bar{d}$	Range	Standard deviation s			Average $\bar{d}$	Range	Standard deviation s	
	in	in	in	in	in	in	in	in	in	in
Best individual										
M	23.75	-0.031	-0.39 to 0.28	0.154	-0.38 to 0.32	19.79	0.018	-0.85 to 1.00	0.381	-0.85 to 0.88
566	22.94	-0.068	-0.36 to 0.23	0.148	-0.40 to 0.27	15.98	-0.163	-0.71 to 0.38	0.231	-0.69 to 0.36
P	24.94	0.023	-0.39 to 0.39	0.174	-0.37 to 0.42	22.91	0.167	-0.54 to 1.41	0.499	-0.97 to 1.30
B	23.24	-0.055	-0.49 to 0.26	0.163	-0.42 to 0.32	18.16	-0.059	-0.55 to 0.45	0.232	-0.59 to 0.47
E	23.20	-0.056	-0.43 to 0.33	0.162	-0.42 to 0.31	18.21	-0.057	-0.57 to 1.31	0.366	-0.89 to 0.77
Worst individual										
A	24.30	-0.006	-0.41 to 1.07	0.278	-0.64 to 0.62	20.15	0.035	-0.49 to 0.76	0.342	-0.74 to 0.81
Q	29.77	0.242	-0.23 to 0.81	0.260	-0.35 to 0.83	19.93	0.025	-0.66 to 0.75	0.403	-0.89 to 0.94
Best two-station combinations										
E + L	24.13	-0.014	-0.13 to 0.24	0.067	-0.17 to 0.14	18.80	-0.029	-0.37 to 0.88	0.268	-0.64 to 0.58
E + J	24.59	-0.007	-0.13 to 0.16	0.081	-0.18 to 0.19	19.12	-0.014	-0.48 to 1.19	0.311	-0.72 to 0.69
Reporting stations										
721 + 722	24.12	-0.015	-0.44 to 0.25	0.126	-0.30 to 0.27	18.22	-0.057	-0.54 to 0.45	0.209	-0.53 to 0.42
566 + 722	23.43	-0.046	-0.38 to 0.10	0.133	-0.35 to 0.26	17.40	-0.095	-0.66 to 0.67	0.257	-0.68 to 0.49
Best three-station combinations										
566 + 721 + L	24.10	-0.015	-0.11 to 0.10	0.054	-0.14 to 0.11	17.66	-0.083	-0.35 to 0.47	0.174	-0.48 to 0.31
566 + 721 + K	24.25	-0.009	-0.14 to 0.15	0.061	-0.15 to 0.13	18.25	-0.055	-0.32 to 0.28	0.146	-0.39 to 0.28
A + G + P	24.68	0.011	-0.15 to 0.15	0.063	-0.13 to 0.15	21.13	0.082	-0.27 to 0.49	0.174	-0.31 to 0.48
A + L + P	24.77	0.015	-0.16 to 0.08	0.055	-0.11 to 0.14	20.81	0.067	-0.26 to 0.48	0.189	-0.36 to 0.50
Reporting stations										
566 + 721 + 722	23.72	-0.033	-0.25 to 0.08	0.090	-0.24 to 0.17	17.47	-0.092	-0.45 to 0.21	0.177	-0.49 to 0.31
Best four-station combinations										
566 + 721 + L + P	24.31	-0.006	-0.10 to 0.06	0.039	-0.10 to 0.08	18.97	-0.021	-0.40 to 0.31	0.175	-0.42 to 0.38
566 + 721 + 722 + L	24.06	-0.017	-0.10 to 0.05	0.042	-0.11 to 0.08	17.95	-0.069	-0.42 to 0.23	0.148	-0.40 to 0.27
E + B + N + 722	23.80	-0.029	-0.10 to 0.05	0.042	-0.12 to 0.07	18.91	-0.024	-0.31 to 0.24	0.122	-0.30 to 0.25
Reporting stations										
488 + 566 + 721 + 722	23.68	-0.035	-0.35 to 0.16	0.105	-0.27 to 0.20	17.68	-0.083	-0.38 to 0.24	0.137	-0.39 to 0.23

and the probable range is -0.10 to +0.08. Two additional combinations give almost as good results. The combination of the three interior reporting stations with Station 488, adjacent to the watershed, gives poorer results than the three interior reporting stations alone.

For the 21 summer storms the combination of Stations E, B, N, and 722 gives the best results of the combinations which were analyzed, but the probable range is over three times as large as for winter storms, and little better than the three-station combinations for summer storms.



DATA FROM ANALYSIS OF RECORD

NUMBER OF STATIONS USED	PROBABLE DIFFERENCE BEST STATIONS	PROBABLE DIFFERENCE RANDOM STATIONS
1	0.36	0.53
2	0.17	0.32
3	0.14	0.24
4	0.10	0.20

Fig. 2--Probable difference from average watershed rainfall

Random four-station combinations for winter storms give average difference -0.006-inch, range -0.46-inch to 0.46-inch, standard deviation 0.086-inch, and probable range -0.20-inch to +0.19-inch.

Number of stations needed to provide desired accuracy of watershed average rainfall--The curves on Figure 2 show the number of reporting stations needed to provide a given accuracy in estimating average watershed rainfall for winter storms. These curves were developed from the results of the extremes of the probable ranges of the best and random stations and groups of stations. The data used are shown on the chart.

The curves for both best and random stations show a large reduction in the probable difference from average watershed rainfall with the use of two stations over one. Progressively smaller reductions are indicated with a further increase in the number of stations used. Reports from two best stations or four random stations will provide average watershed rainfall with a probable difference of 0.2-inch, which is maximum for the desired accuracy of stream-flow estimates. Average watershed rainfall within 0.1-inch would require reports from four best stations or about ten (extrapolated) random stations.

It is impracticable to obtain this degree of accuracy for the majority of summer storms which contribute very little to stream-flow because of spotty distribution. . The data on summer storms in Table 1 show that heavier summer storms are distributed about as uniformly as winter storms. A rainfall station network which is suitable for winter storms should provide satisfactory estimates of average watershed rainfall for runoff-producing summer storms.

Location of stations--Stations in the best groups are symmetrically located and provide reasonably good watershed coverage. Stations located on interior ridges appear in all but two of the best multiple-station combinations. Such stations record rainfall from storms which are concentrated on either side of the ridge. Some best two- and three-station combinations include no stations located either east of the main interior ridge or in McLemore Cove extending to the southwest, the best four-station combinations include stations in these areas. Stations located on the watershed rim or outside the watershed do not appear in the best combinations. Rainfall observed at such stations is frequently not representative of the watershed average. Because of the uncertainty of the effect of local topography at station sites and the variability of storm paths, the best locations for a group of stations can be determined only by operating a dense network of stations long enough to provide data for making a selection.

Conclusions--These data indicate that rainfall reports from Stations E and L should provide about the accuracy of average watershed rainfall required for river forecasting. However, because the rainfall record available for this study is limited, its is advisable to use the group combination of stations 566, 721, and L which provides better watershed coverage and improve accuracy.

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SMALL THREE-DIMENSIONAL SEISMIC MODELS

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(Publication No. 55, Institute of Geophysics, University of California)

Abstract--The fundamental theory of models is reviewed and application made to the case of three-dimensional laboratory models of seismic phenomena. The nature of usable transducers and media of transmission are considered from the standpoint of the bandwidth restrictions imposed by the modeling method. The experimental prodedure is described and results for a model for Lamb's problem are obtained. The influence of imperfections of elasticity is also investigated; the results for a wax accord with theoretical predictions based upon a viscoelasticity of a simple type.

The geometrical scale of a model of any physical phenomenon may be made as small as desired if control is available over the other, non-geometrical factors entering into the construction of the model. In the case of a seismic model of purely elastic motions in solids, such control is always available and this model may be made arbitrarily small. Because of the lack of information concerning certain physical properties of dissipative solids, it is not certain whether the non-geometrical control is available for a model for a study of motions in lossy or imperfect materials.

For a seismic model of elastic behavior, the relationships

$$\zeta = \alpha\tau \qquad \gamma = 1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

exist between the geometrical scale factor ζ, the time scale factor τ, the velocity scale factor α, and the Poisson's ratio scale factor γ. A scale factor is the ratio between the values of a measured quantity at corresponding points or times in model and prototype. For a three-dimensional model of seismic behavior in an elastic Earth, the range of velocities for solid materials available in both the laboratory and in the real earth is quite limited. Thus geometrical scale reduction is accompanied by a corresponding reduction in the time scale.

$$\zeta \approx \tau$$

If, in the prototype, ranges of the order of kilometers are of interest and times of the order of 0.1 second are the least discernible time intervals in a seismic record, and if laboratory distances are to be of the order of centimeters, then the least discernible intervals in the laboratory system will be of the order of one microsecond. Thus laboratory transmission systems, including sources of motion, amplifiers, etc., must all be broadbanded to at least one megacycle. This is the only restriction upon the construction of a successful seismic model. There are several corollary difficulties.

Laboratory materials to be selected must have similar properties over the frequency range 0 - 1 megacycle as Earth materials have in the range 0 - 10 cps; such assurances can only be obtained by direct experimental verification. Several materials, notably organic solids, have been found to possess resonances or selective absorption near the upper limit of the frequency band or both. Other materials, especially homogeneous samples of various rocks, do not exhibit any anomalous elastic bahavior. Still other materials, in particular a wax described later, have a non-elastic behavior of a regular type over the entire one-megacycle band.

Transducer fidelity for transient operation with microsecond rise-times is a condition which is not always easy to obtain. Receiving crystals are most simply broadbanded by backing with materials matching the acoustic impedance of the crystal using velocities along the axis of the detected motions. This is an approximation which is good for receivers with a narrow lobe in the forward direction. This procedure does not eliminate the generation of resonant shear modes in finite crystals but this latter difficulty is removed by selection of the proper crystal receiver material. For this reason lithium sulfate (LH) monohydrate crystals have been grown, Y-cut, and mounted upon matching backing materials. Both $Li_2SO_4 \cdot H_2O$ and $BaTiO_3$ have been shown to be highly efficient transducers [KNOPOFF and BROWN, 1953] but lithium sulfate has the advantage of low shear coupling and excellent directionality. The receivers described are used only for the detection of the component of motion normal to a bounding surface.

In order to obtain the advantages of high repetition rate oscillography and a high degree of reproducibility of observational results, crystal source transducers have been used. Pulse techniques for crystals, with the aim of obtaining pressure pulses of simple shape with a high degree of directivity, are not at all well developed. Knopoff and Brown have already investigated the directivity problem for pulsed one dimensional transducers and have found solutions for the surface excitation of semi-infinite media by mechanically loading the reverse faces of crystals and by simultaneously applying some unconventional voltage wave forms across the crystal electrodes. Typical waveforms obtained from a generator constructed for this purpose are shown in Figure 1. The pulse width T of the first step is the travel time of sound through the crystal while the ratio of secondary amplitude to primary amplitude is $(Z_1 - Z_2)/(Z_1 + Z_2)$ where Z_1 is the acoustic impedance of the crystal and Z_2 is the acoustic impedance of the load. The doublet width is 2 T.

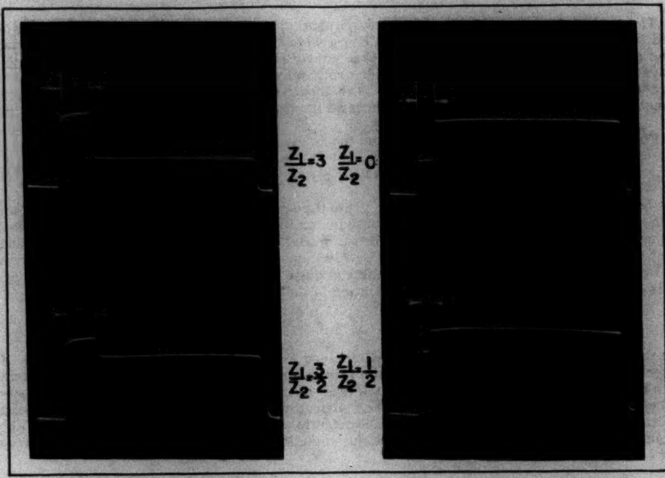

Fig. 1--Voltage waveforms used to excite plane unbacked crystals in order to obtain a doublet stress pulse into the load

Another procedure which seems to succeed for several types of source crystal transducers is the method of diffuse loading. In this method a long, lossy scatterer of sound is used for the conduction of the sound away from the reverse face. Coupling to the scatterer is made through a material matching the crystal impedance in the sense used above.

The pressure pulse duration depends only upon the source crystal thickness and the velocity through the crystal. However, the pulse duration does not influence the frequencies present in the received signal. The frequency spectrum is limited only by the structure modeled and the rise time of the applied voltage pulse. From the above analysis, rise times of the order of one microsecond are sufficient to accomplish successful modeling with the proposed range. From practical experience, however, pulse widths should be either much less than, or much greater than the travel times of P-waves from the source to the first or last receiver stations respectively. The first condition is much easier to obtain in practice; if the first receiver station is more than one cm from the source, pulse widths need be no smaller than two microseconds for typical laboratory materials.

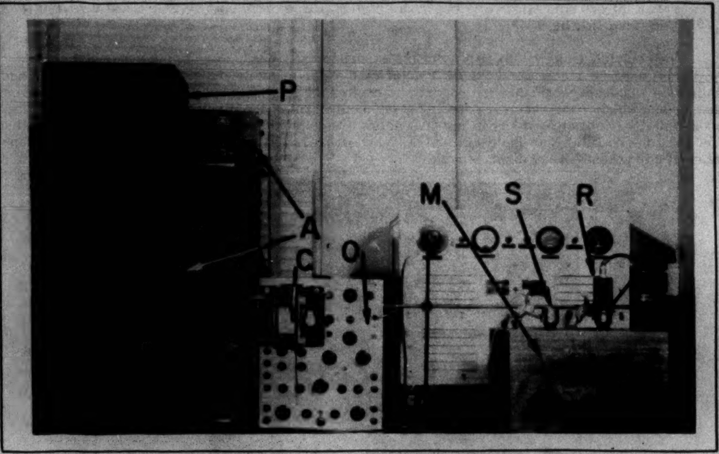

Fig. 2--Experimental setup for a model study of Lamb's problem in wax; A, amplifiers; O, oscilloscope; C, camera; S and R, crystal transducer holders; M, model; P, pulse generator

The experimental setup is shown in Figure 2 in which the scale of a typical model is given. The experimental technique used is not unusual. The source of the excitation is a pulse generator which drives the source transducer and simultaneously provides the trigger impulse of the oscilloscope sweep. Pulse repetition rates are typically of the order of 1000 cps. The seismic signal is obtained from the receiving transducer, amplified and displayed upon the oscilloscope tube face as a quasi-steady state signal by means of synchronization with the input pulse. Long exposure (up to five seconds) photographic records are obtained.

Typical results obtained with a model excited as indicated above are given for one simple example of a postulated structure. These results (Fig. 3) show the response of a homogeneous, isotropic semi-infinite half-space of rigid material to excitation by an impulsive source placed upon its surface. The motions shown are of the component of motion normal to the surface of the half-space when excited by an impulsive force directed normal to the surface and placed at the surface. The scale of the model is indicated by the fact that the spacing between receiver stations is 0.5 cm ranging from 2.5 cm to 12.5 cm. The time scale for this model is given by the sweep rate of 20 microseconds per unit marker distance. The material used was a microcrystalline wax of high molecular weight branched paraffins with no visible structure and no included air bubbles.

The data of Figure 3, results of a model study of Lamb's problem, are investigated in detail. Clearly in evidence are a direct P-wave, a Rayleigh wave and P-P reflections from two horizons: the bottom of the slab and a planar flaw close to the bottom of the slab. No direct S-wave is visible, in agreement with the predictions of LAMB [1904]. The slow wave is identified as an R-wave from amplitude variations, varying, within experimental error, inversely as the square of the range. This value combined with the amplitude variation of the P-wave (inversely as the 2.67 power of the distance) and the R-wave broadening (directly as the 1/3 power of the range) lead to a description of the mechanism of the propagation of energy in the wax. In Lamb's problem for elastic solids the waves broaden directly as the distance; a dissipative model for the propagation in wax is indicated. The data are consistent with a viscoelastic model for the wax [NEWLANDS, 1954] incorporating a hydrodynamic (Stokes) viscosity such that both the viscous and the elastic constants are independent of frequency. The stress-strain relations for this model of the solid are

$$\tau_{ij} = \lambda e_{kk} \delta_{ij} + 2\mu e_{ij} + \lambda' \dot{e}_{kk} \delta_{ij} + 2\mu' \dot{e}_{ij} \quad \ldots\ldots\ldots\ldots\ldots (3)$$

This result differs somewhat from the model of dissipation obtained by WEGEL and WALTHER [1929; see also BIRCH, 1942].

For completeness, the directivity of the experimental transducers, in the sense of Lamb's problem, must be analyzed. We wish to determine experimentally the quality of the excitation and detection and observe whether the source has excited the load with but one component of the stress tensor and whether the receiver detects but one component of the displacement vector. Some degree of reliability is anticipated since the transducers are coupled to the load through a film of oil, thus reducing the possibility of the excitation of shear stresses in the surface and the detection of non-normal components of the displacement.

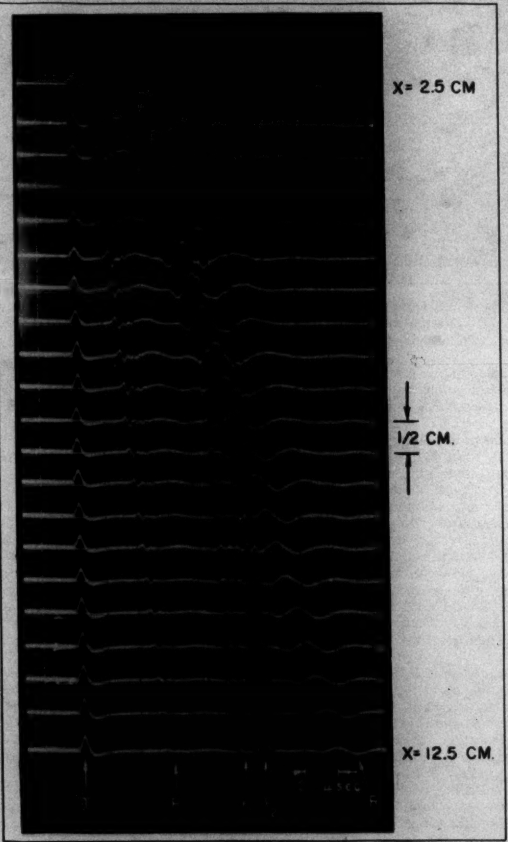

Fig. 3--Observations taken for Lamb's problem in a viscoelastic medium; time and distance scales are given; T, timing break; P, direct P-wave; R, Rayleigh wave; P_1 and P_2, P-P reflections

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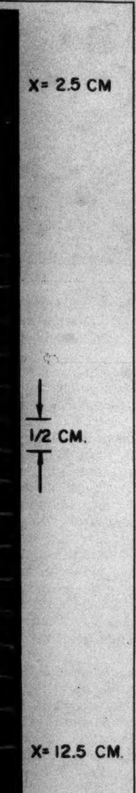

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P-wave; R, Rayleigh

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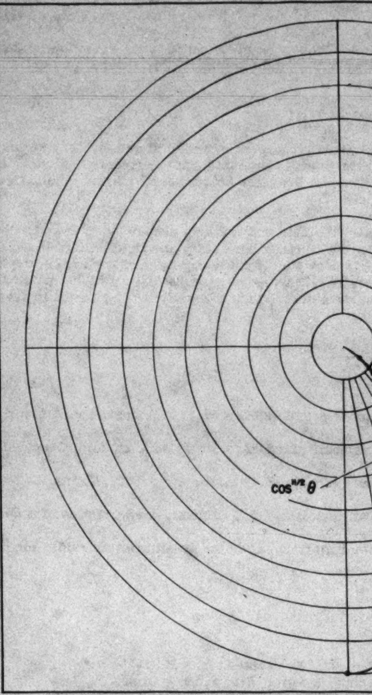

Fig. 4--Experimental observations of amp
LH transducers on opposite sides of

The product lobe of the receiving and source cr
an experiment of the preceding type except that the
lengths thick. In a plane slab of wax, approximately
the case when the transducers are on opposite sides
the lithium sulfate crystals from the measurement
for the energy loss in wax by the coefficients of visc
ment. These results are presented in Figure 4 as
the transducers and the normal to the plane faces.

If the load is perfectly elastic, it is a relatively
fectly directional transducers. However, if the load
of Eq. (3), the product lobe should follow the law co
select between elastic and viscoelastic loads, it see
are very nearly ideal in the matter of directional ex

It is now evident that lack of certainty exists co
control for lossy, or viscoelastic, seismic models.
governed by Eq. (3), the four relationships

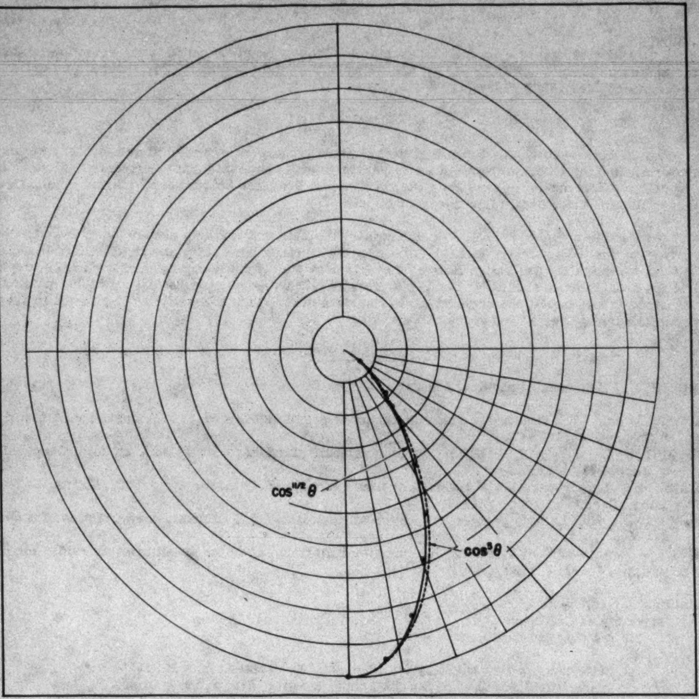

Fig. 4--Experimental observations of amplitudes of P-waves using oil-coupled LH transducers on opposite sides of a 3 cm air-bounded wax slab

The product lobe of the receiving and source crystals may be determined directly by means of an experiment of the preceding type except that the runs are made over a slab only several wavelengths thick. In a plane slab of wax, approximately three cm thick, the motions are obtained for the case when the transducers are on opposite sides of the slab. This experiment gives the lobe of the lithium sulfate crystals from the measurement of the amplitudes of the direct P-wave, corrected for the energy loss in wax by the coefficients of viscoelasticity computed from the preceding experiment. These results are presented in Figure 4 as a function of the angle between the line connecting the transducers and the normal to the plane faces.

If the load is perfectly elastic, it is a relatively simple matter to obtain the law $\cos^5\theta$ for perfectly directional transducers. However, if the load is perfectly viscoelastic, according to the law of Eq. (3), the product lobe should follow the law $\cos^{5.5}\theta$. Although the results of Figure 4 do not select between elastic and viscoelastic loads, it seems clear that the transducers, when oil-coupled, are very nearly ideal in the matter of directional excitation and reception.

It is now evident that lack of certainty exists concerning the availability of non-geometrical control for lossy, or viscoelastic, seismic models. For a seismic model of viscoelastic behavior, governed by Eq. (3), the four relationships

$$\zeta = \alpha\tau \qquad \gamma = 1 \qquad \xi = 1 \qquad \alpha\zeta/M = 1 \quad \ldots\ldots\ldots\ldots\ldots (4)$$

must be satisfied, where ξ is the scale factor for Stokes' number and M is the scale factor for the kinematic shear viscosities μ'/ρ appearing in the viscoelastic Eq. (3). Stokes' number has been defined [KNOPOFF, 1954] as

$$S = (\lambda' + 2\mu')/\mu'$$

It is not certain whether the last two of the relations (4) may be satisfied simultaneously for Earth materials and the laboratory materials requiring reduced kinematic shear viscosity. Further measurements will be made to investigate the spectrum of available Stokes' numbers and kinematic shear viscosities for viscoelastic laboratory materials.

Note added in June 1955--It now seems fairly certain that the loss properties of the wax described in this paper are atypical in comparison with other laboratory and field materials. Further critical investigation has shown that in other cases of pulse broadening in solid materials, the solid friction model for loss [BIRCH, 1942] is preferable. Despite the singular nature of the material described in this paper, the experimental procedure outlined here is sufficiently general to discriminate among the various types of loss.

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DISPERSION OF SEISMIC WAVES NEAR A SMALL EXPLOSION

George V. Keller

Abstract--The characteristics of the ground vibrations caused by the detonation of small dynamite charges were studied at distances from ten to 3070 ft from the point of detonation. The motion which was observed could be separated into several types on the basis of velocity and particle motion paths. The major part of the recorded motion following the arrival of body waves exhibited strong dispersion. A comparison of this dispersion with that theoretically predicted for Rayleigh waves by Love, Sezawa, and others, showed that these motions are probably Rayleigh waves of the first and second types. The complex particle motion orbits observed near the shot point are probably a result of the overlap of these two normal modes of surface wave propagation.

Introduction--The nature of the vibrations of the surface of the Earth near an explosion is becoming of increasing interest to people in a wide variety of fields. Geophysicists have a primary concern with the subject in view of the rapid growth of the seismic reflection method of prospecting in the past twenty years. It has long been realized that the motion of the ground near an explosion is a complicated mixture of various surface and body waves. These waves have been studied by LEET [1939], who observed several types of motion which were not readily correlatable with the waves predicted by theory. One of the types described by Leet consisted of in-phase motion observed on three orthogonal recording components. In studying seismic waves generated by the explosion of an atomic bomb, LEET [1946] also observed waves consisting of vertical and longitudinal components with a sense of particle motion corresponding to gravity waves in a liquid. Leet chose to call the first type 'coupled' waves and the second type 'hydrodynamic' waves. Both these types of waves exhibit dispersion, as pointed out by HOWELL [1949]. The latter observer noted also that the coupled wave exhibited a change in velocity with distance from the shot point, resembling refraction. This last characteristic would be expected of body waves but not of surface waves. In addition, the particle motion of the hydrodynamic and Rayleigh type waves was elliptical in sense with axes being tilted often at an angle of about 45° to the surface of the ground.

The observations of Leet and Howell illustrate the nature of the problem. The vibrations which have been observed close to the source of a small explosion are so complex in nature that they are not readily identifiable as any of the classical types of motion predicted by theory. The question arises as to whether this lack of correspondence between theory and observation can be resolved by the extension of existing wave-propagation equations to the actual conditions existing near an explosion, or whether a different mathematical approach is necessary. The object of the present research was to study these vibrations of the surface near an explosion and to attempt to explain them. Three orthogonal components of ground velocity were recorded at distances between ten and 3070 ft from small explosions. In studying the records so obtained, particular emphasis was placed on the dispersion of the waves and on particle trajectories, since these two properties of surface waves may serve readily as a basis for their classification and identification.

Very little work has been published on the generation of seismic surface waves near an explosion. However, the literature on surface waves from earthquakes is voluminous. The existence of wave motions associated with a free surface and traveling with velocities less than those of body waves was first demonstrated mathematically by RAYLEIGH [1885]. LOVE [1911] explained that the long oscillatory nature usually observed for surface waves was caused by dispersion, an increase of velocity with an increase in wave length. He showed that this dispersion is the result of the presence of a surface layer with lower elastic constants than the underlying media. Love's analysis, and the resulting equation for the dispersion of Rayleigh waves, have been the basis for almost all of the subsequent work on the dispersion of Rayleigh waves.

SEZAWA and KANAI [1935 ab] discovered a second solution to Love's equation for Rayleigh wave propagation. It differed from the first solution in that the sense of particle motion was direct rather than retrograde, and the energy was accumulated near the lower boundary of the overburden.

Sezawa and Kanai identified these waves, which they chose to call M_2 waves, on records of the Great Indian earthquake of January 15, 1934. SEZAWA [1938] considered the surface displacements for both solutions. He found that the M_2 waves correspond to a resonance-like condition of body waves being transmitted through the surface layer. The waves of the second type are prominent only for very large ratios of elastic constants between the two layers, such as exist between soil and bedrock.

Further efforts were made by KANAI [1948], HOMMA [1951] and HOMMA and NISHIZAWA [1952] to identify M_2 waves on records of earthquakes. In addition, in the last of these papers the authors indicate that there are more than two solutions to the Rayleigh wave equation, each of the branches corresponding to waves having a definite number of modal planes within the overburden. This result has been substantiated by TOLSTOY and USDIN [1953], who used an interference method of obtaining the surface wave dispersion equation.

HOWELL, NEUENSCHWANDER, and PIERSON [1953] have pointed out that the work of the Japanese seismologists can probably be extended to explain the wave motion observed by LEET [1939, 1946] and HOWELL, [1949].

Experimental observations--The data used in this research were recorded on the farms of the Pennsylvania State University, approximately two miles north of the campus. The area is one of low, rolling hills, with a relief of about 100 ft. Because of the topography, the thickness of the soil mantle probably is not uniform.

The bed rock underlying the soil is predominately limestone and orthoquartzite of Cambrian age. The area of the survey lies on one limb of the Gatesburg anticline, which dips at 9 to 18°. The area left much to be desired in uniformity of character, but it met the basic requirement of the problem admirably, having a very large contrast between the elastic properties of the weathered layer and the bedrock. This is illustrated by the core logs and an in-hole velocity survey which was carried out in the same area, shown in Figure 1.

The equipment used in recording the ground motion was similar to that used commercially in seismic prospecting. Three refraction seismometers, having a natural frequency of 3.5 cps, were used at each recording location; one responding to vertical motion and the other two to transverse

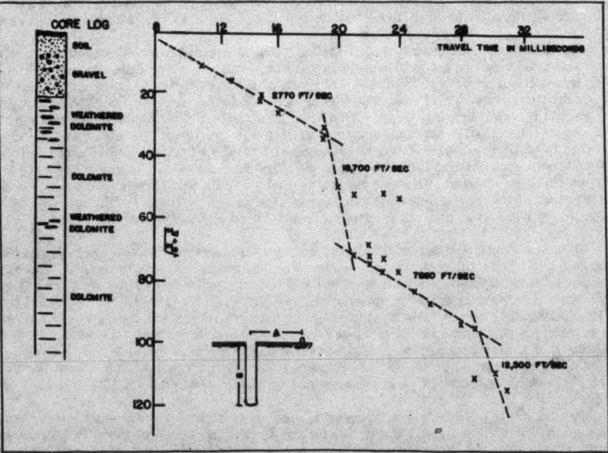

Fig. 1--Sample log and in-hole velocity measurements from one of the drill holes used in seismic field experiments and longitudinal motion. The output of the seismometers was fed into resistive attenuating networks for seismometer locations at distances less than 200 ft from the shot point, and into three stage triode amplifiers at larger distances. An oscillograph was used to record the ground motion.

The shots, each consisting of one pound of 60 pct dynamite (Hercules Vibrogel), were detonated in drill holes at depths between eight and 18 ft. The charges were stemmed with several feet of water. A total of 125 records was made of the ground motion at distances between ten and 3070 ft from the shot point. Examples of several of the records are given in Figure 2. The first of these records was taken at a distance of ten feet from the hypocenter, and shows a short burst of high frequency energy on all three components. The second record, at 196 ft, illustrates the splitting of the single pulse into several wave groups. On this record, the first arrival no longer has the largest amplitude, but the maximum arrives about 0.12 sec later. The other two records, taken at 573 ft and at 1620 ft show well developed surface waves persisting for two to three seconds.

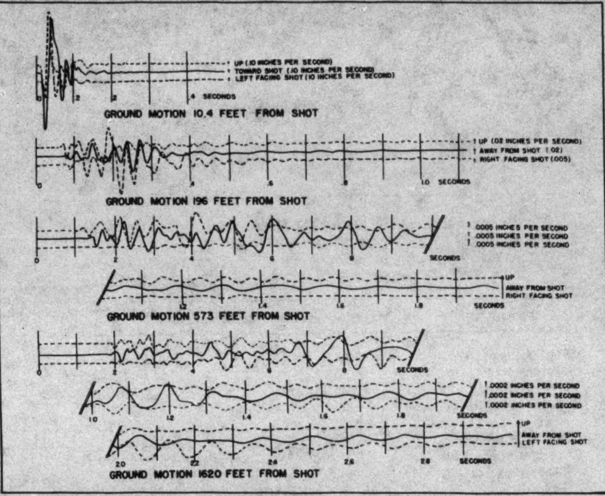

Fig. 2--Records of ground motion at 10.4, 196, 573, and 1620 ft from the shot point

Travel-time curves--The first step in the study of these records was the construction of travel-time curves. Figure 3 is a plot of the arrival times of the first compressional and shear body waves. Using formulas given by MACELWANE and SOHON [1932], these curves were used to calculate the velocities nad thickness of the several layers, as well as the elastic moduli. The results of these computations are listed in Table 1.

Following this, a travel-time curve was constructed for all of the recorded wave forms which had characteristics by which they could be traced. The results are shown in Figure 4. At distances of 600 ft and greater, these data appear to group into three categories, each of which is characterized by different phase velocities. On Figure 4, these groups are denoted as A, B and C for reference purposes. Group A, which persists for about 0.3 sec following the first arrival, is characterized by a high phase velocity, about 16,000 ft/sec. It is reasonable to conclude that these are refracted body waves, in view of their high velocities.

Group B is characterized by velocities considerably lower than those of Group A, with the velocities decreasing from a maximum of 4000 ft/sec for the first apparent phase of this group through values of 3700, 3000, 2800, and 2300 ft/sec for succeeding phases. Following Group B and intermingling with late arrivals of group B, there are waves, designated on Figure 4 as C, having very low velocities. These velocities vary from a maximum of 1420 ft/sec to as low as 640 ft/sec.

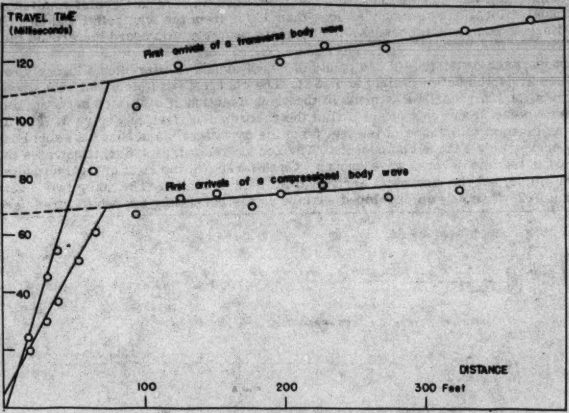

Fig. 3--Travel-time curves for the first arrivals of compressional and shear body waves

Table 1--Assumed and derived elastic properties

Parameter	Value for surface layer	Value for the underlying medium
Thickness	38 ft	Infinite
Velocity of longitudinal waves	1080 ft/sec	13,100 ft/sec
Velocity of shear waves	630 ft/sec	7,300 ft/sec
Poisson's ratio	0.245	0.273
Assumed Density	125 lb/cu ft	163 lb/cu ft
Coefficient of rigidity	49.6×10^6 lb/sq ft	86.8×10^8 lb/sq ft
Lame's constant	58.0×10^6 lb/sq ft	106×10^8 lb/sq ft

At distances closer than 600 ft, the travel-time curves cannot readily be divided into the three groups. The velocities are much less than those observed at larger distances, varying continuously from about 1660 ft/sec for waves corresponding to the beginning of group B to values as low as 190 ft/sec for waves corresponding to later arrivals in Group C.

Fourier analyses--The second stage of the analysis of these data was a study by Fourier analysis of the frequency content of the various wave groups. Approximately 100 intervals of interest were selected from the records and analyzed by the twelve ordinate method [SCARBOROUGH, 1930]. These analyses were then compared graphically with an analysis of a pure sine wave in order to determine the period and amplitude of the sine wave which corresponded most closely with the section of the seismic record which had been analyzed. This was accomplished by plotting the harmonic amplitudes of an analysis against the harmonic frequencies on a logarithmic plot, and superposing these points on a similar graph for an analysis of a pure sine wave (see Fig. 5). The experimental plot was laid over Figure 5 and moved about until all of the experimental points fell on or near the appropriate curves. This permitted the determination of the frequency and amplitude of the sine wave which came closest to having the same harmonic analysis as the unknown function. Unless some such procedure is used, the amplitude of the various coefficients in the Fourier series will depend on the length of record chosen for analysis, even without variation in the frequency of the waves being analyzed.

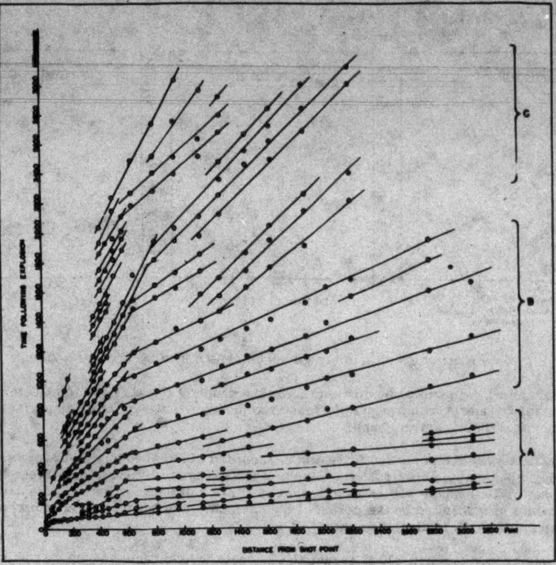

Fig. 4--Travel-time curves for all principle seismic waves

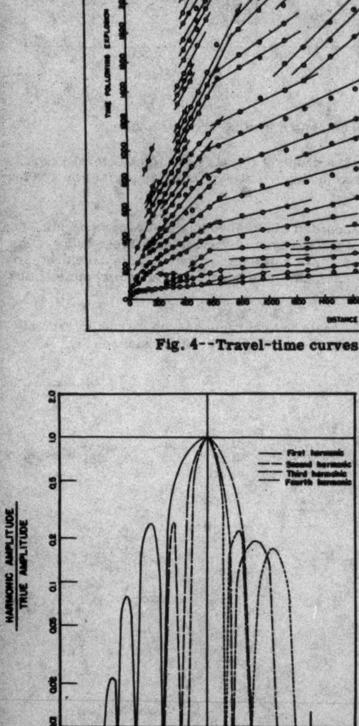

Fig. 5--Curves for amplitude as a function of frequency for the first four harmonics of a Fourier analysis of a pure sine wave

Among the wave forms so treated were 34 analyses of the first arrival of seismic energy on the vertical and longitudinal components, 25 analyses of Group B and 14 analyses of Group C. In Figure 6, the apparent frequencies found by these analyses are shown as a function of the hypocentral distance. In all cases except for the first arrival of the direct body wave at distances less than 200 ft, the frequency decreases with distance, as might be expected. However, at distances less than 200 ft, the frequency of the first arrival remains constant.

Particle motion diagrams--A further basis for the classification of these three wave groups is the nature of the orbits followed by particles at the surface of the ground at the time of arrival of seismic energy. This can be studied by plotting the displacements recorded on the transverse or vertical component against the simultaneous displacements recorded on the longitudinal component. The result is a graph of the projection of the actual ground motion on a horizontal or vertical plane. In these experiments, ground velocity rather than ground displacement was measured. If a plot is made of simultaneous ground velocities in two dimensions, the resulting graph is a velocity hodograph of the ground displacement. The shape

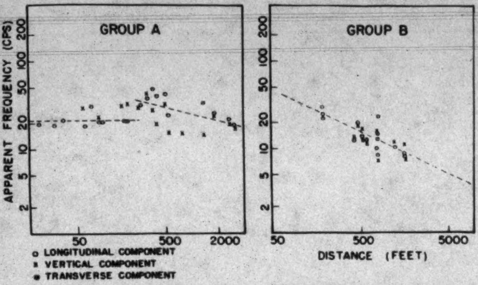

Fig. 6--Frequencies of seismic waves as determined by Fourier analysis

of this hodograph will in general be different from the shape of the particle displacement graph, since the higher frequency components of ground motion are relatively more important on a velocity graph than on a displacement graph.

If Fourier analyses are computed for motions recorded simultaneously on two components, then velocity hodographs may be constructed for each of the harmonic frequencies. These hodographs will be ellipses. Their shape will be exactly that of similar graphs for particle displacement, and if each harmonic is multiplied by the period of the harmonic, the hodographs will become identical with the graphs for particle displacement.

The seismic record taken at 820 ft serves to illustrate the character of the motion in each of the three observed groups, since they are all fairly well represented at that distance (Fig. 7).

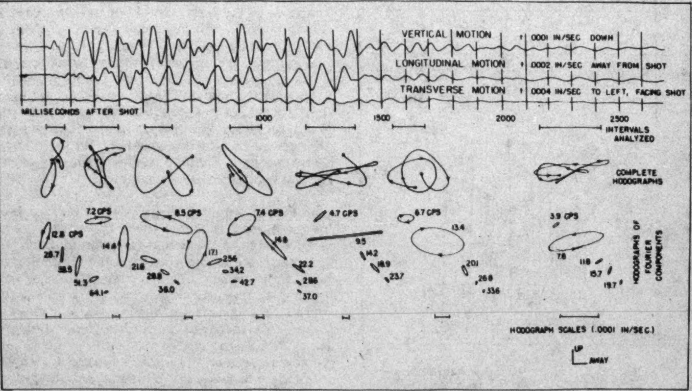

Fig. 7--Particle motion graphs at a distance of 820 ft from the shot point

The first particle motion diagram illustrates the first arrival of seismic energy, which upon decomposition is seen to be mostly compressional waves arriving from below. These fit very well the characteristics to be expected of a refracted body wave.

The second diagram is also a wave from in Group A. The Fourier decomposition of this wave form indicates that it may be the sum of a refracted wave arriving almost vertically and a second wave, possibly a shear wave, which is horizontally polarized. This may be the first of the surface wave motions.

The next three wave forms analyzed fall in Group B on the travel-time curves. The first consists of two retrograde elliptical orbits of different frequencies, with the one of lower frequency having the largest motion in the vertical direction. This is evidently the beginning of the principle surface wave motion, possibly overlapping the late arrivals of refracted body waves.

The second analysis of Group B shows again that there are two pulses arriving simultaneously, one of low frequency consisting of direct elliptical motion with a slightly inclined axis, and one of higher frequency with the vertical and horizontal components in phase. The third wave form of Group B presents a similar picture except that the horizontal motion is large compared to the vertical. This last hodograph typifies the motion called coupled by Leet.

The last two intervals analyzed belong to wave Group C. The beginning of this motion is characterized by direct elliptical motion of low frequency, with the vertical and longitudinal components about equal. This is a characteristic hydrodynamic wave. The later arrivals in this group consist of retrograde ellipses elongated in the horizontal direction, the characteristics of a conventional Rayleigh-type wave.

Dispersion--The final stage of the analysis of the records was the comparison of the data with the classical theory for surface wave propagation. The Rayleigh-wave dispersion equation as formulated by SEZAWA [1938] was evaluated using the elastic parameters listed in Table 1. The results are presented in Figure 8 in the form of phase velocity plotted as a function of wave length. A multiplicity of solutions were found for the equation, but only those solutions corresponding to the five lowest modes were worked out. They are denoted on the graphs by the symbols M_1, M_2 . . . . M_n, using the nomenclature of Sezawa and Homma. In addition, two non-dispersed branches were found as degenerate solutions, and are denoted as T_0 and L_0 solutions. The L_0 branch consists of a shear surface wave traveling with the velocity of compressional waves and the T_0 branch consists of a compressional surface wave traveling with the velocity of a shear wave.

The L_0 branch may be represented on the seismic records as the deflection recorded on the transverse component simultaneously with the first arrival on the other two components. If it were not for the existence of the L_0 surface wave, no motion would be expected to appear on the transverse component until the arrival of the shear body wave. The T_0 branch is probably represented in a similar manner by motion on the vertical and longitudinal components at the time of arrival of the shear body wave. However, its existence would be difficult to determine because of the other motion arriving at the same time on the other components. The M branches of the dispersion equation are probably represented by Groups B and C on the records, as will be seen from an analysis of the dispersion data.

The seismic field data were compared with the theoretical dispersion curves by determining the phase velocities and wave lengths from the seismic records. Wave lengths and phase velocities were taken from the records for all pulses belonging to Groups B and C which could be correlated between successive records with a good degree of reliability. Examples of these data at various distances from the shot point are shown in Figure 8. These points showed general agreement between the overburden thickness as indicated by the dispersion data and as indicated by delay times and by several electrical resistivity surveys which were made in the same area. At the larger distances, where the assumption of plane-wave propagation is essentially valid, the correspondence between the data and theory is particularly good. Close to the shot, however, the surface waves apparently do not penetrate deeply enough to be affected by the bedrock, and the dispersion is apparently caused by the contrast in elastic constants between a thin soil layer and the rest of the weathered layer. The dispersion data at distances less than 150 ft from the shot point indicated that the velocity of compressional waves in this near surface layer may be as low as 190 ft/sec.

In most cases, the bulk of the data falls along the curve of least wavelength for a given frequency. For short wavelengths (group C of the travel-time curves), this lower curve is the M_1, or conventional Rayleigh-type branch, and for the long wave lengths (Group B), this is the M_2 branch.

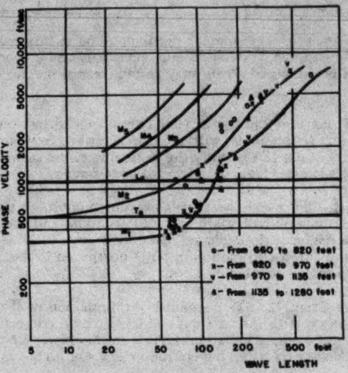

Fig. 8--Dispersion data for records taken between 660 and 1280 ft from the shot point

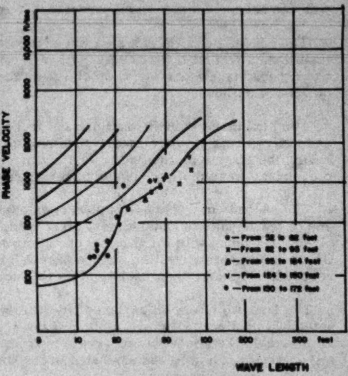

Fig. 9--Dispersion data for records taken between 52 and 172 ft from the shot point

The separation is not complete, since a few points fall along the curve having the second lowest values of wave length. The inference is that Group B consists mostly of M_2 waves while Group C consists mostly of M_1 waves, but both types of motion are present in both groups to a greater or lesser extent.

Summary--In the research which has been described in this report, the velocities of transmission of seismic waves in a soil layer near a small explosion have been studied. The conditions of these experiments paralleled closely those of LEET [1946] and HOWELL [1949], who identified wave types designated as coupled and hydrodynamic as well as the more conventional types.

In order to compare the data obtained in the present experiments with the theory developed by Love, Sezawa, and others for surface wave propagation, the Rayleigh-wave equation was numerically evaluated for the case of a single overburden having the elastic properties indicated by the observed body wave velocities. The observed data were found to agree reasonably well with theoretical dispersion curves. The agreement between the data and the theory is particularly striking when it is remembered that the theoretical computations were carried out under the assumptions of plane wave propagation in a perfectly elastic medium.

On the basis of dispersion data, it seems reasonable to conclude that except for the early, high-velocity waves, all or almost all of the vibrations resulting from an explosion are surface waves satisfying classical seismic wave propagation equations. The waves may present a more complex picture than is realized in earthquake seismology, since near an explosion there is not time for the different wave trains to be separated by their distinctive group velocities. As a result, two different modes arrive at a given point at the same time, resulting in such motions as figure-eight particle paths. That these peculiar orbits are merely coincidence and not distinct wave forms is indicated by their failure to be preserved from record to record as are the simpler wave forms.

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SOME OBSERVATIONS ON VERTICAL TECTONICS IN AFRICA

B. B. Brock

Abstract--A review of the fundamental structure of Africa puts the emphasis on vertical tectonics, which has resulted in an 'embossed' shield. Basins and swells, troughs and rims, pans and domes, all are manifestations of epeirogenesis or tafrogenesis. All types of depressional features are compared and unified: the Rhodesian type of basement remnant, basins, troughs, gently folded mountains, and geosynclines. All these depressions are thought to result from the same type of fundamental forces in varying degree. The process in the early stages involves only vertical tectonics. Compression where present is induced, it is postulated, by these tafrogenetic processes when carried to excess. Such an hypothesis explains epsilon shaped ranges, and the spidery basement remnants with diverging isoclinal trends. It can account also for the occurrence of folding and thrusting in some rift valleys, and its absence in others. Here, it is thought, is the link between orogenesis and tafrogenesis.

Introduction--An understanding of African structure is difficult, if not impossible, unless one thinks in terms of vertical tectonics. The local reception of 'The Vredefort Ring' [BROCK, 1950] was sufficiently chilly to indicate that a great many geologists do not think in such terms, and also cool enough to have discouraged a worker from proceeding further along such lines unless he were certain that he is right in the essentials. That paper was a stepping stone to broader horizons. Analagous structures at different stages can be found throughout Africa, and particularly in Rift Valley country. This led to 'An Approach to the Rift Valley Problem' [BROCK, 1952] which attempted to show that South Africa is indeed a good approach to the Rift Valley question, that Rift Valleys are not the prerogative of East Africa, that most of the important tectonic events happened in the Precambrian, and the subsequent ones reflect Precambrian structures; that repeated movements on pre-existing faults have controlled the story of the geology of Africa since then.

The trend of thought, thus far, involved working outwards from an intensively studied area into wider fields and then attempting to unify the whole. In the present paper it is proposed to start from a broad unified picture, and work down the scale, to show that the varied subdivisions are all variations on a theme.

Some definitions pertaining to the embossment of a shield--The geological term 'shield,' applying to the rigid Precambrian nucleus of a continent, was presumably culled from heraldry. In recent times the term has often been used to apply to any small Archaean rigid block, even though it constitutes only a very small proportion of what normally is thought of as the shield. Let us return to heraldry for a more precise definition.

The basins and inset blocks correspond so perfectly to heraldic 'charges' that the geological meaning surely must embrace all the embossments, embellishments and 'devices' right out to the limit of the Precambrian rims. A basin, however large, if it is surrounded by a rim of Archaean rocks, becomes just an embellishment of the shield. The subdivision of Africa into minor shields is thus terminologically incorrect. The whole of Africa south of the Sahara extension of the Mediterranean is a shield, as is Australia west of the 140th Meridian.

Africa's 'full achievement' in the heraldic sense is of a low order, in that the shield is the dominant feature. This distinguishes Africa from the 'ideal continent' which has a small nucleus or shield with a mantling fringe of relatively undisturbed rocks, and on one coast or both an immense orogenic belt.

WILSON [1950] describes the growth of a continent. Africa is abnormal in that it has not grown; on the contrary, it is apparent that chunks of Africa have been lost, for instance, the easterly end of the Cape Foldings, and the southerly flank of the trough which contained the Table Mountain sediments.

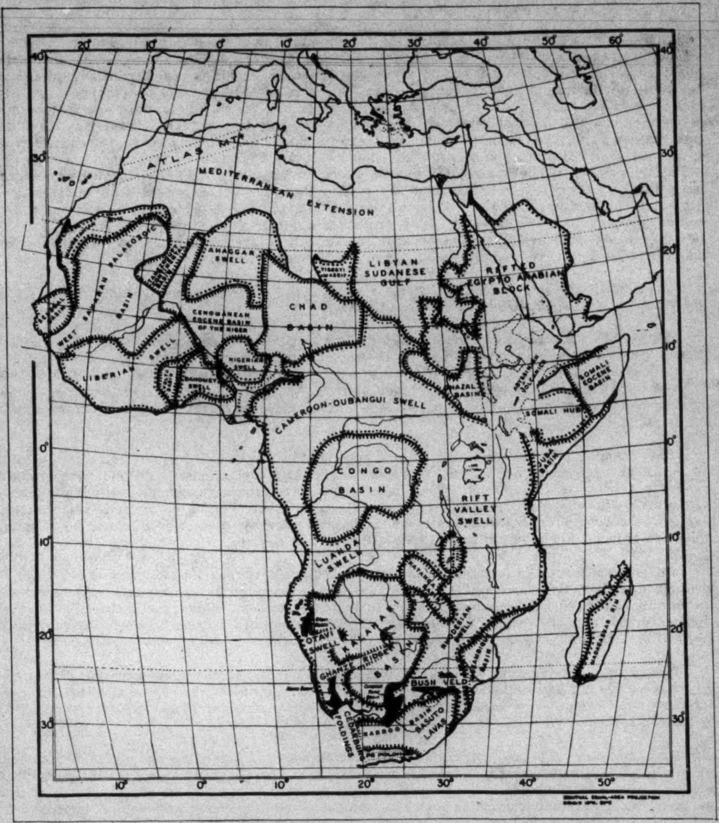
ATLAS MT.
MEDITERRANEAN EXTENSION
WEST SAHARAN PALAEOZOIC BASIN
AHAGGAR SWELL
TIBESTI MASSIF
LIBYAN SUDANESE GULF
RIFTED EGYPTO ARABIAN BLOCK
CHAD BASIN
CENOMANEAN EOCENE BASIN OF THE NIGER
WEST SWELL
LIBERIAN
NIGERIAN SWELL
DAHOMEY SWELL
HAZAL BASIN
ABYSSINIAN VOLCANIC
SOMALI EOCENE BASIN
SOMALI HUB
CAMEROON-OUBANGUI SWELL
CONGO BASIN
JUBA BASIN
RIFT VALLEY SWELL
LUANDA SWELL
KATANGA
RHODESIAN SWELL
OTAVI SWELL
KALAHARI BASIN
GHANZE RIDGE
MOZAMBIQUE BASIN
MADAGASCAR RIB
BUSH VELD
BASUTO LAVAS
BASIN
KARROO
CEDARBURG
FOLDINGS
20°
10°
0°
10°
20°
30°
40°
50°
60°
40°
30°
20°
10°
0°
10°
20°
30°

Fig. 1--Tectonic map of Africa showing basins and swells after the manner of E. Krenkel with modifications

The German school of thought, led by Krenkel and H. Cloos, paved the way towards a better understanding of African structure, putting the emphasis on basin and swell structure. The tectonic map (Fig. 1) is modelled on the ideas of KRENKEL [1925, p. 19] and HOLMES [1944, p. 429] denuding Africa of irrelevant details, such as veneers of younger sediments which obscure the fundamentals.

Africa (or for that matter any part of Gondwanaland) can be divided into negative and positive areas: the basins and swells. There is very little, if any, neutral ground and the balance between the two, areally, is remarkably even.

Since we have dropped the term 'shield' for subdivisions of the major shield area, 'swell' should be adopted in its place. Acceptance by HOLMES [1947, p. 429] of the term should be sufficient recommendation, and if it has not come into general use, this is possibly because of an undesirable implication of liquidity or linearity. 'Bulge' is an appropriate synonym conveying the idea of a 'protuberance'; both these words are common English usage requiring no explanation, but neither is a suitable technical term with which to adorn a tectonic map. 'Swell,' on the other hand, has an established place in geologic literature and, in its technical sense, the counterpart of a basin, there need be no ambiguity. A linear swell might become a 'rim,' 'arch,' or 'ridge.' A smaller swell or kernel, more or less equidimensional in plan, might alternatively be designated a 'hub.' 'Massif' has an implication of mountain masses only rarely applicable in Africa. 'Dome' is confined to cases where the quaquaversal dip approaches perfection. There are many domes in Africa, usually relatively small, measurable in miles or, more rarely, scores of miles. Beyond that size they are apt to be truncated by major structural breaks, and with the perfection thus impaired, the terms 'hub' or'swell' become more appropriate.

The negative areas give less occasion for ambiguity. 'Basin' is used in the tectonic, not the topographical sense. More will be said of this later.

An analysis of African structure involves the study of the processes of the embossment of a shield. The word 'embossment' is used to embrace the processes of vertical tectonics causing the ups and the downs - (the downs being regarded as 'embossing towards the middle,' as allowed by the Oxford English Dictionary, Unabridged Edition). The processes include the sinking of blocks forming troughs, basins, swamps, etc. and the uplifting of blocks forming plateaus, horsts, swells, and rims.

The essential combined embossing processes could be called small scale epeirogeny, vertical tectonics, or tafrogeny. 'Epeirogeny' from its root refers to continents as a whole, in their bodily movements, hence is not the most appropriate term for the processes which entail a fine mosaic within the continent. 'Vertical tectonics' meets the case precisely, but is clumsy in that no adjective can be derived from it. Reluctantly we resort to 'tafrogeny' derived from the Greek meaning trough or trench. For a definition PICARD [1939, p. 5] is quoted:

> The vertical forces on the other hand (in distinction to orogenic) find expression in a more rhythmic up and down movement of the Earth's crust demonstrated in the formation of tumour-shaped elevations. Tafrogenetic phenomena account for ruptures in the Earth's crust and lead to the formation of big and little rift valleys and oceans. The components of tafrogenetic movements are mainly vertical, but can also to a limited extent become tangential forces shifting the Earth's crust.

The major subdivisions of the shield are the larger basins and the intervening rigid blocks (or cratons) which Cloos calls "unities of relatively inert structure more or less welded into one another by ..... axes of very varied development." He elaborates this idea as follows [translation by HUME, 1948, p. 280]:

> The assumption of primary areas among the continents and seas takes account of a crust composed of polygonal plates which are hinged together. In the more inert plates, relatively little happens, but all the more varied is the behaviour at their boundaries, the hinge zones, where are worked out the vertical and the horizontal movements, the extensions, the pushings together, the transverse and relative stretching movements of the plates. Here occur the geosynclinal depressions, the geanticlinal elevations, the diaper-like upheaving of deeper-seated material, the dissection by faults and outpourings of magma.

The hinge zones thus defined are important tectonic belts, and the term, in English at any rate, is far from perfect. The geological hinge action is much more complex than the door hinge, and there need not be tilting or swinging involved. The essential idea can be summarised quite succinctly: Relatively rigid polygonal plates making up the Earth's crust are held in position areally by gravity and friction; tectonic activity, be it vertical or horizontal, is most intense on the edges of the plates, and it may take a variety of forms and give rise to a variety of after-effects.

Cloos's hinge zone is related to WILSON's [1950, p. 13] 'lineament,' that ill-defined but necessary term. Because the structural significance of a lineament is too vague or too varied, the term became necessary. A lineament, for the purposes of this paper, is an alignment of varied structural features most or all of which have a probable intimate relationship with a deep seated fracturing, yet in the absence of observed faulting can be called neither fault nor fault zone. One can suppose however, with a fair degree of confidence, that a well-developed lineament represents a deep seated crustal fracture now largely obscured by subsequent events.

Lineaments, on the surface, are more unidimensional than hinge zones. A narrow hinge zone could be regarded as a lineament; the broader ones may be bounded by parallel lineaments.

The tectonic sense of the term 'basin' confines it thereby to depressions in the crust, usually deduced from the infilling of younger sediments. There is commonly an overlapping with geomorphological or drainage basins, often of the same name (for example, Congo). The boundaries of a drainage basin can be defined with precision, whereas the boundaries of the tectonic basin are often conjectural, obscured by a veneer of younger sediments, or modified by erosion. Where uncertainty exists because of an interlocking of younger with older rocks, the smaller of the alternative shapes of the basin is likely to be more important structurally because the younger sediments have a tendency to be spread thinly over the plateau with very little structural meaning.

The Karroo is a case in point. Areas of rocks correlated with the Karroo system are spread widely over Africa south of the Sahara, but these do not help us to define the Karroo basin proper. Where the Karroo succession is incomplete and thin, the knowledge that the underlying Precambrian is not deeply buried is more significant information for the present argument than the extent of the veneer.

The eroded rims of the sediments filling the basin too frequently provide the only cross sections, but in certain cases connected with the mining industry where sections have been obtained nearer the center there is stratigraphic and lithologic evidence to suggest that there have in the past been gross overestimates of the degree of erosion. The present outlines of basins are not far removed from the original. In the particular cases studied, structural evidence ties in well with that conception.

The basins and swells of Africa--The conspicuous internal basins of Africa are the Kalahari, the Congo, and the Chad, of fairly uniform size with a 700 - 900-mile diameter. The Karroo, the Ghasal and Niger Basins are the next in order of size, and the straightness and angularity of their boundaries betray the structural controls.

The three major basins and the Karroo are aligned meridionally up the west central part of Africa in an orderly fashion, leaving a Precambrian rim to the westward and a broader mass including the Rift Valley and Rhodesian swells to the eastward. The basins are separated one from the other by swells of Precambrian terrain, which constitute for the most part rigid structural units, broken here and there by structural depressions such as the Limpopo and Zambezi valleys, and the Rift Valley system. The resulting pattern is one of repeated basins and swells, a pattern of a pleasing design, which makes repeated use of the same sort of dimensions, and results in a nice balance between the positive units and the negative ones.

The same could be true on other scales, but the older and generally smaller basins tend to be partly covered by younger basins, the evidence (but not necessarily the basin) is more fragmentary. The Transvaal basin, over the major part of which the Bushveld subsidence is superimposed, offers some real evidence concerning its ultimate limits at least as concerns the lobe protruding clear of the Bushveld basin. In this appendage of the Transvaal basin, mining exploration has allowed of a three dimensional view denied to us in other truncated rims.

Black Reef conglomerate which outcrops more or less continuously over many miles was shown by forty boreholes to peter out rapidly down dip. The conglomeratic facies, quite linear in its development, must be a feature of shallow water deposition along the lip of the basin. Its parallelism to a well marked upthrow fault (the Buffelsdoorn Fault), a few hundred yards away over a matter of twenty miles or more, suggests that the Buffelsdoorn Fault marks the actual lip, and that the amount of Black Reef lost by erosion is relatively small. The basin here at least is almost intact.

The source rocks for the Black Reef clastics in the western Transvaal must have been very restricted as the greater part of the area was, at the time of their deposition, covered with Ventersdorp lava. Only a few horsts can have projected above the level of the lava, which would account for the very attenuated clastic beds in the west. To the east where the Ventersdorp is missing and the granite rim much in evidence, the Black Reef quartzite measures thousands of feet, against thirty to fifty feet in the west. The local source of sediments confirms the restricted initial size of the dolomite basins.

Other areas in South and Southwest Africa characterized by dolomite are the Campbell Rand, the Otavi, and the Nama areas which could be significant segments of individual basins. Lithological and chronological evidence supports this contention. A considerable portion of each basin is obscured by younger rocks but enough is visible to get a fair idea of the dimensions of at least one side of each. There is a similarity between these dimensions, ranging between 350 and 400 mi, comparable also with the length of the Bushveld basin. This dimension holds roughly also for the intervening granitic bulges. Indeed the basin pattern is almost mathematical in its intermittent arcuate arrangement around the fringes of the Kalahari basin. The relationship to hinge zones is evident, with implied structural control.

The prevailing idea of a Transvaal Ocean extending over the greater part of the continent is thus seriously questioned.

It is not known how dolomites or limestones were deposited in continental basins at shallow depths (oolites are common in the dolomites) but the strict principles of uniformitarianism do not necessarily apply. The atmosphere for one thing may have been at the time highly charged with CO_2, with little or no vegetable life to absorb it.

The accumulation of thousands of feet of dolomites (10,000 ft at Otavi) in restricted continental basins demands drastic vertical tectonics.

The limits of the Katanga Basin have remained undefined. When absolute age determinations become more numerous and more dependable, the Series des Mines (Bwana Mkubwa or Roan Series) may prove contemporaneous with, for instance, the Black Reef and the Transvaal dolomite. But in the light of vertical tectonics this would become rather an academic question as the basins concerned, separated by vast tracts of Archaean rocks, may never have been joined by a continuous series of beds.

It behoves us then to attempt to outline the Katanga basin, the results of which are recorded on Figure 1. The method involved (1) a consideration of uplifted rims of older rocks, (2) the assumption that the coarse conglomeratic material of the Lower Bwana Mkubwa series is not far removed from its source, and (3) the conception (already mentioned and at least locally proven) that the degree of erosion over the face of Africa has been greatly overestimated in the past.

The Lomagundi and Broken Hill - Lusaka beds are interrupted only by the Zambezi depression, as DU TOIT [1954, p. 175] has stated. To the westward the Kalahari hides what is probably only a small corner of the basin.

In spite of local lack of definition the shape as mapped is thought to be a reasonable approximation. It conforms in general shape with better defined basins. In size it is bigger than, but comparable with the Transvaal basin and others of late Precambrian age, and much smaller than those of Mesozoic and Tertiary age.

Numerous other basins include the Witwatersrand Basin, described elsewhere BROCK [1954]. This is overlapped by that lobe of the Transvaal Basin which was not affected by the Bushveld subsidence. The overlapping of structural basins makes clear portrayal difficult on the present scale. The lines of overlap are commonly structural lineaments of some importance.

The Bangweulo Basin, a more recent subsidence marked now by a lake and its surrounding swamps, focuses attention on the correlation of the Plateau series and Luitikila beds, which might be Bwana Mkubwa, Kundelungu, or Muva. Need they be any of these three series? Their symmetry with relationship to the lake makes it seem plausible that the present lake is a vestige of a larger inland basin that once embraced the area now covered by these sediments.

Lake Victoria could be a roughly comparable case of a younger age. The topographical basin has a comparable symmetry about the present lake whose structural control is proved to some extent [SHACKLETON, 1950].

The Okavango delta is a small filled basin. The structural control of this is apparent in the fault scarp across its toe [DEBENHAM, 1953, p. 93] in the same hinge zone that controls also the mid-Zambezi rift, and the Ghanze ridge which nearly cuts the Kalahari Basin in two. This inland delta is the site of numerous recent earthquakes [GANE, 1953, Pl. IV].

From their size, shape, and character many of the larger pans, such as Etosha and Makarikari, can be classed as incipient basins, and many smaller pans may be variations of the same phenomenon.

A review of the tafrogenetic characteristics of Africa--The principal mode of deformation in Africa involves nearly vertical fractures. The angular and linear mosaic scarcely allows of anything else.

The structural control of basins is most evident where most detailed work has been done: the Zambezi Valley coal basin, the upper Witwatersrand Basin, and the Transvaal Basin; also the Nyasa Rift. That it applies equally to all basins is suggested by the linearity of the westerly Ghasal limb, the triangular aspect of the Chad, the linear easterly edge of the Kalahari, and the angular pattern of the Karroo Basin, to quote just a few examples. The habit is ubiquitous.

The difference between a basin and a linear trough is essentially one of size and shape. Both entail the dropping of a block, causing a depression which in due course becomes filled. The habit of bounding faults to work in parallel pairs is evident on all scales. The habit is particularly conspicuous in the case of rift valleys only because they are young enough not to have been filled. Their counterparts, the uplifted blocks like Ruwenzori, are conspicuous too because they are young enough not to have been eroded down. Similar tectonic forms have been found in fossilized form: filled rift valleys and truncated horsts now buried by flat lying rocks.

The larger manifestations of the same processes, the basins and swells, were never as spectacular as the young rifts, and the controlling structures are now largely hidden. Underground work in the gold fields has helped in providing evidence that we are indeed dealing with the same type of tectonics that produced the rift valleys.

The tectonic map should be studied as an expression of vertical tectonics, that is, an exposition of ups and downs. There is a harmony about the ups and downs, to be observed on all scales. The major basins and the major swells are areally nearly equally balanced. The Rift Valley zone of East Africa bounded by arcuate fault zones is a unit comparable in area to its counterpart the Congo basin. The basins and swells make a pleasing, almost mathematical pattern.

Cloos [HUME, 1948, p. 390 ff] advocated a quantitative study of structure, having noted a certain constancy in the size of major basins, and also a suggestion of constancy in the ratio of a rift width to the rigid block which it traverses. Holmes likewise has commented on the uniformity of rift widths.

On this theme it is interesting to note that the broader basins in general are of comparatively recent origin and that the late Precambrian basins are comparatively small, while the Archaean sedimentary remnants are diminutive. In the last case it is realized that the extent of the original sediments cannot be deduced from the fragmentary evidence of the remnants, but the miniature vertical isoclines that remain are a striking contrast to the immense geosynclines of Palaezoic and later times.

It is suggested that in a general way there is a tendency towards an increase in dimensions of structural units with decreasing age, which implies a thickening of the crust with the passing of time.

The major units of structure are pictured as fragments resulting from the breaking up of a rigid mass, and the size or mass may, in a general way, be a function of the thickness of the crust (ignoring subcrustal conditions). A simple analogy is found in the sampling of diamond drill core which involves first breaking the core into convenient lengths. A casual blow with a hammer on homogeneous massive quartzite tends to produce a standard length, a function of the diameter of the core. An attempt to get a length shorter than the standard requires patience, skill, and cunning. The same sort of control, it is suggested, could apply to the fineness or coarseness of the polygonal mosaic.

The conception of a crust increasing in thickness is compatible with the observation that basins and geosynclinal troughs get broader, deeper, but sparser. It would imply that many of the innumerable Precambrian fractures have become more or less sealed or healed, and that the rigid units likewise have become greater in dimensions. The idea of stiffened blocks has been expressed by others [HUME, 1948, p. XLIII].

The combination of basins and swells after the manner described by Cloos presents a generalized but accurate picture of the embossed shield. In detail, too, the scheme is generally similar, except that locally compression has come into play. Let us then turn our attention to evidences of compression in Africa.

Orogenesis in Africa--Evidences of compression in Africa can be put into several categories: (1) late Precambrian hinge zones, and small folded basins; (2) Archaean basement remnants; (3) the Cape foldings; (4) the Atlas mountains; and (5) the restricted evidences of compression in certain rifts.

Folding and thrusting in varying degree occurs at numerous places throughout Africa, confined usually to narrow straight belts generally of late Precambrian age. Examples are the Prieska folding, the Ghanze ridge, and the east-west belt north of the Bushveld, all of which are post Waterberg; the Nama folding and the Outjo thrust related to the small dolomitic basins; the Katanga folding and thrusting which is most intensive in the Katanga itself. Many examples can be cited, and they share the same linear belt-like character as though confined between parallel faults, they line up with other linear structural features, and they are commonly related to the boundaries of larger basins, and may comprise lobes of smaller basins.

The rigid crystalline rocks which form shields may and do yield, failing by fracture more usually than by flowage. When they do yield the break is apt to be abrupt and linear, and is confined to a narrow zone. The belt-like zones of rupture are the hinge zones, which combine to control the embossments of the shield. The first category hinge zones bounding major shields may be represented by orogenic mountain chains.

The Archaean areas in Africa (and those throughout the world) have characteristic basement remnants deeply inset in granite (Fig. 2). The remnants are for the most part rather fantastically shaped: hook shaped (barbed hooks at that), crescent shaped, anchor shaped, claw shaped, spider shaped, and irregularly shaped. (It is here that names of heraldic devices might be aptly applied.) It is at once apparent that no succession of horizontal forces can be devised to account for the numerous narrow isoclinal prongs which project in any and every direction.

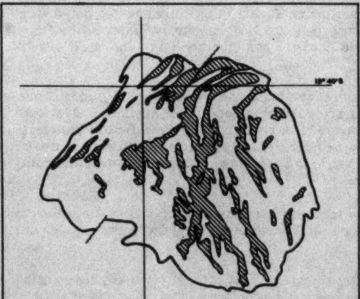

Fig. 2--Granitic dome with remnants of basement sedimentary schists East of Kafue, Northern Rhodesia; mapped by W. Garlick

MacGREGOR [1951, p. xxxix] pertinently observed that the set-up was akin to a piece of paper floating on a pond on which a stone had been dropped. The essential parts of the simile are: (1) that the beds were never thick, and (2) that gravity was the principal force involved. The triangular remnants with concave sides he regards as the hiatus between three circular granite domes, which fits the case well for that particular shape. But most of the shapes are much more complex than that.

If these are the roots of old mountain chains (a cliché whose popularity is hardly warranted) the mountains were in miniature, the chains short and unattached - links that linked nothing - and the causal stresses extremely local. Each pair of forces must have been confined to its own little syncline. This conception is quite in keeping with that of a thin crust which precludes the possibility of a geosyncline of the dimensions of those of Mesozoic and Tertiary times. With the thin crust the stresses appear to have found relief more easily and ubiquitously, resulting in the finicking Rhodesian pattern.

The pattern of the Cape foldings is bolder than that of Archaean, but it does not compare with the modern geosynclines, and it shares the Rhodesian habit of abrupt and angular changes of strike (see Fig. 3).

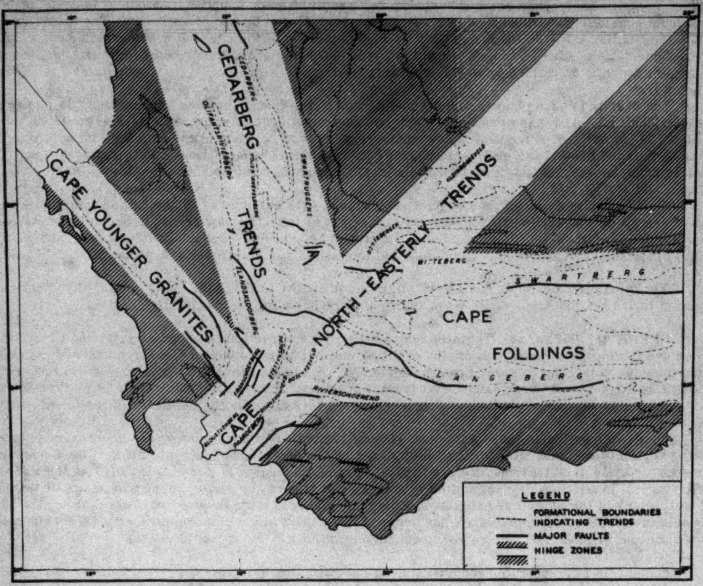
CEDARBERG TRENDS
CAPE YOUNGER GRANITES
NORTH-EASTERLY TRENDS
CAPE FOLDINGS
CAPE
CEDARBERG
OLIFANTSRIVIERBERG
SWARTRUGGENS
ELANDSKLOOFBERG
WITTEBERG
SWARTBERG
LANGEBERG
RIVIERSONDEREND
BLOUSTEENBERG
PAARDEBERG
LEGEND
FORMATIONAL BOUNDARIES INDICATING TRENDS
MAJOR FAULTS
HINGE ZONES

Fig. 3--'Epsilon' structure, Cape province

There are three distinct trends framing the lobe of southern Africa. The junction of the East Cape and the Natal trend is now beneath the sea just off the coast, but there is no room for a sweeping arc. It is an angular join. The junction between the main Cape mountains and the Cedarberg ranges is fortunately well exposed. The two do not quite meet. Between them is a distinct northeasterly trend thirty miles wide represented by the Bontebergen, Klein Roggeveld, Bloustéenberg, Paardeberg, Stettynsberg, and Boschjesveld. The short chunky ranges, each with a different name, are characteristically block-faulted mountains, not a folded range. The normal Cape trend does not peter out; it ends abruptly against this fault-bounded zone at an angle in plan of 45°. The Cedarberg ranges likewise terminate suddenly at this same buffer.

The tectonic pattern is not unlike the epsilon-shaped mountains in China described by LEE [1939, p. 296]. There is, in fact, a fourth trend converging on the same focus, the line of granitic intrusions between Paternoster and Agulhas.

The compression in the Cape mountains and Cedarbergs, strong by African standards, must be a subsidiary feature to the faulting which controls the trends. Four radiating mountain chains meeting at a spot near Worcester cannot be accounted for by any pair of forces, rotational or compressional, nor could it be a succession of regional forces, without leaving evidence of such a succession. Each range has its own set of forces, the compressional forces being induced, it is suggested, by processes related to the faulting which controlled the sedimentation of the Table Mountain sediments which have built up the epsilon arrangement.

Possible link between orogenesis and tafrogenesis--It now remains to find a mechanism by which compressive forces come into action as a result of being bounded by vertical faults. Here we must consider the Alpine type of structure as exemplified by the Atlas range. The formation of a geosyncline involves the dropping of an elongate block of the crust at a rate which keeps ahead of sedimentation. This is in keeping with all types of subsidences described. But here the process has gone on until something revolutionary occurred.

Whatever the cause of the dropping of the floor of the trough, it does happen; there is no argument about that. And there must have been an abundant source of sediments to keep the trough filled. The downward movement of the trough is of a distance measurable in miles, an approximation of the thickness of the sediments deposited. This floor segment finds itself in a very much hotter environment, its lower portion amongst truly igneous conditions in the substratum.

The dropped segment of the crust, it is assumed, gets eaten away by melting in this environment until it no longer qualifies as a rigid part of the crust. The new accumulated sediments above are anything but rigid. The rigid sides of the trough become in effect the jaws of a nutcracker. The subsided and weakened block buckles, and the contents of the trough get squeezed.

This hypothesis demands but a very slight modification to **HOLMES** [1944, p. 382] hypothetical section through a mountain range - the addition of the bounding faults of the geosyncline.

JEFFREYS [1952, p. 302 ff] states that the Earth's contraction is adequate to account for the intensive folding of the mountain chains of the world, but he is emphatic that the measured compression involves something besides crustal shortening. A homely simile is the contents of a tube of toothpaste squeezed out vertically by horizontal pressure: the length of the ribbon of toothpaste is no indication of the actual amount of compression, as measured by the diameter of the tube.

The above hypothesis may be an over-simplification, but it does answer the question of translating vertical into horizontal forces. It disposes of the problem of mountain arcs. These are not 'festoons'; their original troughs were formed by combined pairs of parallel faults, like the rift valley arcs. In addition, the postulated processes can stop at any stage, hence can be applied equally well to any of the other examples of less intensive compression between parallel faults. The one stipulation is that the dropped block has dropped far enough to have become weakened. A relatively small amount of pressure may restore equilibrium, allowing the action to cease.

Here surely is a possible reconciliation in the rift valley controversy. It supplies a plausible answer to the successive operation of vertical and horizontal forces, with the emphasis very much on the former. The latter in many instances may never come into play. The rift is essentially the result of tafrogeny, but if the process is carried far enough, the compressive forces are induced, and manifestations of compression may be observed, not usually enough to obscure the essential tensional aspect, but sufficient at all events to have led to one of the most complete disagreements in the history of the science.

In summing up, the five types of depressed blocks of the crust vary only in size, shape, and degree of compression. The amount of compression varies from nil through moderate folding and thrusting to Alpine manifestations characterised by nappes. The greatest other variable which controls the degree of folding is presumed to be the thickness of the crust. If it be acknowledged that Archaean folding (however intense) is of a small scale fine pattern involving innumerable local trends, and rarely if ever the broad sweeping curves of the modern geosyncline, this can be taken as evidence of a thin crust in Archaean times. If such be so, then it would not be surprising that geosynclines get bigger, and revolutions more revolutionary with the passage of time and the thickening of the crust.

Note on the history of structural geology--The principles of structural geology were evolved largely in the more spectacular environments of the folded regions of the world: the Alpine ranges and the Highlands of Scotland, the Appalachians and the Cordillera. Tafrogenetic effects in the folded mountains have long been recognized. Geosynclinal troughs are acknowledged to be depressional features, and the post folding uplifts which leave marine fossils on mountain tops are acknowledged to be vertical uplifts.

What has been lacking is the recognition that the compressional effects are subsidiary to the vertical ones. The compressional effects, the spectacular folding and thrusting, obscure the fundamentals.

The German school, with a background of rift tectonics at home, and a two-fronted assault on the geology of Africa, had a realistic approach and set a lead that South Africans have been very slow to follow.

Africa contains the answer, and Cloos [HUME, 1948, p. 281] realized this. The fundamentals are laid bare. Yet narrow little belts of disturbance separating almost undisturbed rock masses are commonly referred to as 'orogenies'; or what is perhaps more misleading is an aggregate of many short discontinuous belts with barely a suggestion of a common trend being classed as a wide orogenic belt. Without quibbling about the appropriateness of the term, African Precambrian'orogenies' are puny by Alpine or Cordilleran standards. These narrow disturbed belts are Cloos's hinge zones. Since they constitute practically the only evidence of compression throughout the greater part of Africa, between the Atlas and the Cape, then surely the subject of vertical tectonics is worthy of greater consideration than it has received. Cloos's sentiments will bear reiteration. Africa is the continent in which to get down to the fundamentals of structural geology.

Instead of trying to force African geology into the pattern developed in Europe and America, let us observe how Africa was made, and if necessary evolve new principles.

The role of geophysics--How best can geophysics help in the development of this theme? The question is best answered by the geophysicist, and it is with some diffidence that the author dares mention two or three aspects which might be followed up. The first is the configuration of basins, which are likely never to be accurately outlined without the help of geophysics (or excessively deep drilling).

The other aspect is the present seismological record which tends to underline the hinge zones. Certain hinge zones which were arrived at on the basis of known geology are not only confirmed but proved positively to be still active as tectonic adjustments. There is evidence, too, of suspected hinge zones being active under the thick Karroo covering. With the help of seismology they become much more real. The importance of structural lineaments, hitherto vague, now stands out clearly.

It is of the greatest significance that the intersection of two hinge zones blocks out an area of intense and repeated seismological activity. One such case, already mentioned, is the Okavango swamp area; another is an area in South West Africa between Swakopmund and Windhoek.

GANE [1953, p. 31] has said that epicentres in South Africa do not appear to be related to 'mountains,' referring presumably to escarpments; that is, topographical as distinct from tectonic mountains. The tie-up between epicentres and hinge zones clearly confirms the view that the hinge zones are the African equivalent of tectonic mountains.

The gravimetric aspect is more complex. Caution is advocated. It has been stressed elsewhere BROCK [1952, p. 235] that the elevated blocks and the depressed blocks of the crust do not always owe their position to their respective specific gravities. The ups and the downs, with or without accompanying volcanic activity, are more or less confined to a hinge zone as far as that particular region is concerned: that is to say, the rigid blocks on either side are tectonically rather inactive. The varied tectonic activities within the hinge zone are interrelated; that is, the ups and downs are complementary and the outpouring of lava may vitiate or reduce the active uplift of blocks. My plea is that gravimetric anomalies be considered in the light of this.

The only statement that can be made at this juncture pertaining to gravimetric work is that anomalies are likely to be in the hinge belts, not in the rigid blocks, and that if anomalies are found in rigid blocks, then the blocks are likely not as rigid as we had thought.

Conclusion--The tafrogenetic character of Africa, where orogeny is of secondary importance only, makes this continent ideal for getting down to fundamentals. It allows of a study of pure vertical tectonics, and of incipient and restricted compressional tectonics; it reveals epsilon-shaped compressed features, through which it provides a possible link between vertical and horizontal tectonics. The former is the fundamental process, the latter is consequential, and thought to be induced by the former. If this hypothesis be correct, vertical tectonics constitute not only the keynote of African structure but of the whole world.

This would result in something of a paradox. The great orogenic regions of the world are also the most tafrogenetic. They are the mobile belts in every sense of the word, with mobility both vertical and horizontal. Africa merely appears to be the most tafrogenetic of continents because it never indulged in excessive tafrogeny, hence the ups and downs have not been obscured by after-effects.

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HEAT FLOW AND DEPTH OF PERMAFROST AT RESOLUTE BAY, CORNWALLIS ISLAND, N. W. T., CANADA

A. D. Misener

Abstract--The program of diamond drilling carried out by the Dominion Observatory and the Meteorological Division, Department of Transport at Resolute Bay during the summers of 1950 to 1953 permitted the placing of thermistors at various intervals to a maximum depth of 650 ft. The thermal conductivity of core samples was determined by the divided-bar method. The average conductivity combined with the high reciprocal gradient (25.4 m/°C) give a value of the heat flow toward the surface of $2.9 \pm 0.4 \times 10^{-6}$ calories cm^{-2} sec^{-1}. Extrapolation of the temperature versus depth graph indicates that the permanently frozen region extends to a depth of 1280 ± 10 ft.

Introduction--The heat flow toward the surface is one of the few directly measurable quantities that are of assistance in forming reasonable hypotheses regarding the interior of the Earth. To give geophysically useful results this quantity must be determined at sufficiently numerous and widely distributed points on the Earth's surface. In recent years determinations have been made for a fair number of locations on various continents and ocean floors in the temperate and tropic zones but, for obvious reasons, not in the Arctic and Antarctic regions.

When the Dominion Observatory, in co-operation with the Meteorological Division, Department of Transport, undertook a program of drilling at Resolute Bay, N. W. T. (74° 41′ N, 94° 54′ W), it was found possible to include arrangements to record temperatures from the surface to a depth of 650 ft. This was the maximum depth attainable with the equipment available and was reached only after repeated attempts and many discouraging set-backs. The drilling procedures and program are described in a report by BREMNER [1953]. Thermometers were placed at various depths in the surface layers; at five-foot intervals to a depth of 70 ft; at ten-foot intervals from there to 100 ft; and at 50-ft intervals to a depth of 650 ft. In all, nine different bore holes were used, all located at the same general site, well removed from the buildings of the settlement. This report will be concerned primarily with the measurements obtained at depths greater than that showing significant annual fluctuation of temperature (approximately 60 feet). The large number of readings at shallower depths will be considered only when discussing certain minor points.

The temperature measurements--The temperature-sensing elements were thermistors whose temperature-resistance relation was determined, at atmospheric pressure, by the Meteorological Division before being taken to Resolute and inserted in the drilled holes. Previous experience with this type of element indicates that it is stable. The resistance of these elements, determined by a multi-channel bridge, specially designed and constructed by the Meteorological Division, could be converted to temperature readings with an accuracy of better than 0.1°C. The temperatures recorded cannot, however, claim this order of accuracy because the magnitude of the effect of pressure on the temperature-resistance relation is unknown.

It has been shown by MISENER and THOMPSON [1952] that the application of pressure to a similar type of thermistor changed its resistance, although the temperature was held constant. A pressure of 1200 lb/in^2 changed the resistance by an amount equivalent to that produced by a temperature change of 0.3°C. This effect increased at lower temperatures. Practically all of the change occurred between one and 30 atmospheres with very little additional decrease in resistance caused by higher pressures.

At Resolute the thermistors were subjected to the pressure of ice freezing in the drill hole shortly after they were placed. This pressure is several orders of magnitude greater than the hydrostatic pressure on the deepest thermistor and so it can be assumed that all thermistors are subjected to a high but unknown pressure. As they are all at about the same temperature (only 5°C variation from top to bottom), it can therefore be assumed that they all would have about the same pressure correction. Because no determination of the pressure coefficient of the thermistors used is available from the U. S. Bureau of Mines who supplied them and their calibration, we will use the recorded temperatures as given by the calibration at atmospheric pressure. The resulting temperature gradients will probably be quite accurate but the individual temperature readings and depth of permafrost will be slightly suspect. These remarks apply, with equal validity, to the gradients and temperatures reported by MacCARTHY [1952] for the region near Barrow, Alaska.

It is beyond the scope of this paper to discuss the numerous instances where thermistors have been used to determine temperatures and temperature gradients under moderate and high pressures. If the pressure-resistance relation is unknown for the thermistors used, the results will not have the accuracy indicated in the temperature-resistance calibration at atmospheric pressure. In cases where all the pressures involved are high and nearly constant (thermistors frozen in drill holes, thermistors close together at the bottom of deep water, etc.) the temperature gradients are probably well determined but the temperatures themselves in error by an unknown amount. In cases where the pressure is variable (hydrostatic pressure in vertical drill holes, etc.) even the gradients may be in error by a significant amount.

The thermal disturbance caused by the drilling operations will be severe because of the necessity of continually circulating hot water through the drill hole. Sufficient time must elapse after the cessation of drilling to allow the region of the hole to regain thermal equilibrium with its surroundings before the recorded temperatures can be considered as representing the undisturbed condition. In Figure 1 are shown the temperature-time curves for a number of points in the last hole drilled. It is evident that during the period of the last three months shown, the temperatures below 100 ft have remained unchanged within the limits of measurement and, therefore, thermal equilibrium has been regained and the temperatures can be taken as representing the undisturbed state. For holes drilled in previous years the records show constant temperatures after the first year so it does not seem necessary to apply either the theoretical expression presented by BULLARD [1947] or the curve fitting technique of MacCARTHY [1952] to determine the undisturbed temperature. As is to be expected, the region at a depth of 100 ft took longer to regain thermal equilibrium than regions at greater depths.

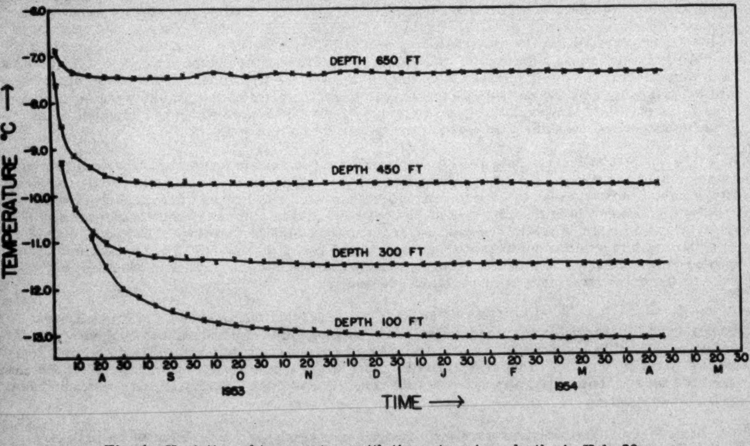

Fig. 1--Variation of temperature with time at various depths in Hole 20, Resolute Bay, Cornwallis Island, N. W. T.

The temperature gradient--The increase of temperature with depth at the Resolute Bay location is shown in Figure 2. Most of the readings are from different depths in the 650 ft hole (Hole 20). The temperatures at depths of 450 ft and 300 ft are confirmed by thermistors placed at the

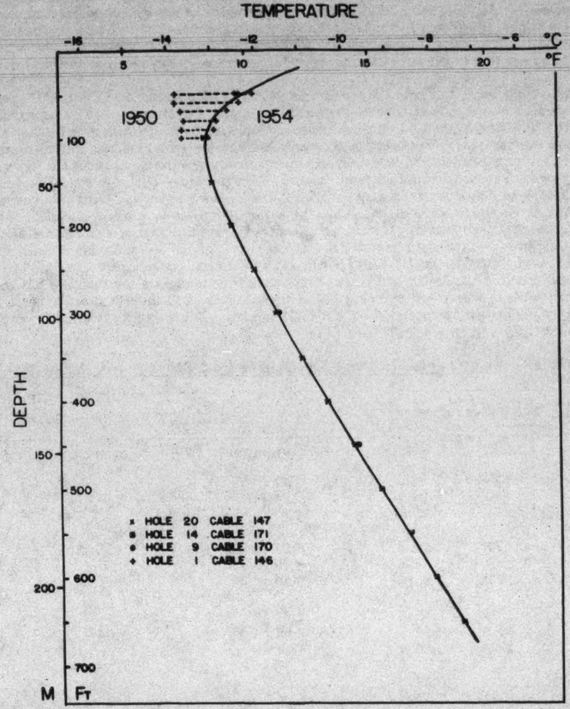

Fig. 2--Increase of temperature with depth at Resolute Bay, Cornwallis Island, N. W. T.

bottoms of Holes 14 and 9 respectively. From a depth of 300 ft down the temperature-depth curve is seen to be a straight line with a reciprocal gradient of 25.4 m/°C (46.3 ft/°F). This is in good agreement with the values found by MacCARTHY [1952] at Barrow, Alaska, but is from 1/3 to 1/4 the values reported by MISENER, THOMPSON, and UFFEN [1951] for locations on the southern edge of the Canadian Shield. The upper portion of the curve in Figure 2 will be discussed later.

Thickness of the frozen layer--The thickness of the frozen layer may be estimated by extrapolating the straight line portion of Figure 2. Such extrapolation indicates that the 0°C isogeotherm lies at a depth of about 1270 ft (387 m). The uncertainty in the pressure correction to be applied to the thermistor readings of temperature make this value probably too low by an amount of the order of 10 to 20 ft. We therefore estimate that the thickness of the frozen layer is 1280 ± 10 ft. This is in good agreement with the values reported by MacCARTHY [1952].

Thermal conductivity measurements--The thermal conductivity of the rock in which the above gradient was observed was determined by preparing samples from five cores taken at different depths and measuring their thermal resistance with a divided-bar apparatus. This apparatus was calibrated with quartz discs by BENFIELD [1939], and its instrumental constant has been checked several times by Bullard, Niblet, and the author. With rock samples of nearly the same diameter as the bar (1.3808 in) it can be expected to give thermal conductivities to within one per cent. Unfortunately the cores from Resolute were considerably smaller (0.87 in in diameter) and a large correction had to be applied to convert the observed temperature differences to thermal resistances.

For samples of nearly the same diameter as the bar this correction is made by simply multiplying the observed thermal resistance by the ratio of sample cross sectional area to bar cross sectional area. Physically, this implies the assumption that all heat flowing in the bar flows uniformly through the sample. For samples of nearly the same size as the bar this assumption introduces a negligible error but it can be seriously questioned when the sample size differs significantly from the bar size. To obtain some estimate of the effect produced by large variations in sample diameter, a series of discs of pyrex glass, 0.250 in thick, were cut with diameters varying from 2.00 in to 0.50 in. As these were all cut from the same sheet it was reasonable to assume that they had the same thermal conductivity. This was measured using the disc of 1.3808 in diameter, the same size as the bar, and found to be 0.00295 cal/cm deg C at 25°C, which agrees with the value for pyrex obtained by BIRCH and CLARK [1940]. The observed conductivity of the others was corrected using the ratio of the areas and it was found that for discs smaller than the bar the correction was certainly valid within ten per cent. For discs larger than the bar the 'corrected' results were not in agreement with the value for the 1.3808 in disc. The results obtained from the cores taken at Resolute Bay are shown in Table 1.

Table 1--Thermal conductivity of rock cores from Resolute Bay, N. W. T.

Core depth	Sample	Thickness	Diameter	Thermal resistance	Thermal conductivity	Density
ft		inch	inch	(arbitrary units)	10^{-3} cal/cm sec deg C	
145	1	0.2372	0.8880	7.09	6.6	- - -
	2	0.4008	0.8900	8.44		
	3	0.5742	0.8890	14.02		
300	1	0.1202	0.8611	5.95	6.9	2.77
	2	0.1696	0.8614	6.48		
	3	0.2963	0.8614	9.58		
400	1	0.1022	0.8740	1.97	8.0	2.69
	2	0.1614	0.8691	3.05		
	3	0.2204	0.8684	4.33		
500	1	0.1472	0.8697	2.99	7.8	2.76
	2	0.2051	0.8709	4.21		
	3	0.2951	0.8709	5.54		
600	1	0.1931	0.8703	5.43	7.5	2.67
	2	0.3140	0.8683	8.36		
	3	0.5094	0.8691	11.95		

The average value of $7.3 \pm 0.7 \times 10^{-3}$ cal/cm sec deg C is probably slightly low as the rock in situ was at a lower temperature and a higher pressure than that of the samples measured. Corrections for temperature and pressure effects upon thermal conductivity would be less than the ten per cent uncertainty mentioned above. Since the temperature gradient shows no changes in slope and since all the cores appear to be the same argillaceous limestone [THORSTEINSSON and FORTIER, 1954], there seems no valid reason not to average their conductivities to obtain a value characteristic of the region. Because of the small number of cores measured, this average conductivity value cannot claim a high degree of accuracy, but it is probably good to ten or 15 pct and is not an unreasonable value for this type of rock.

Heat flow--The product of gradient and conductivity give a value for the heat flow of 2.9×10^{-6} cal/cm^2 sec. This value is considerably greater than the flow reported for any other region and is more than twice the value of 1.2×10^{-6} cal/cm^2 sec, which is becoming accepted as typical of the normal sea-level crust [BIRCH, 1947; 1950]. Even if allowance is made for the relatively large uncertainty in the conductivity value, the heat flow is much greater than that found elsewhere. A reasonable estimate of the likely limits of accuracy in the value of the heat flow would be 0.4 cal/cm^2 sec.

Minimum temperature--An unusual feature in Figure 2 is that the minimum temperature occurs at a depth of about 100 ft. This is well below the level at which seasonal fluctuations become negligible. With heat flowing into this region from above as well as from below it is certainly warming up, a condition that can not have persisted for any appreciable length of time. This minimum was first noted in the 1954 records of the deep hole (Hole 20) and a similar indication was observed in the temperature-depth curves of MacCARTHY [1952]. A preliminary report on the temperatures at Resolute Bay [THOMPSON and BREMNER, 1952] indicated a minimum temperature of -13.5°C at a depth of 50 ft in Hole 6. They also noted that, in 1950, the layer from 50 ft to 98 ft was nearly isothermal.

In an effort to get additional information relative to this problem the temperature records from Hole 1 (maximum depth 98 ft) were inspected.

These extended over the period from 1950 to 1954 and showed that the temperature between 50 ft and 100 ft had been rising during that period (Fig. 3). The magnitude of this rise is indicated by dashed lines connecting the 1950 temperatures and the 1954 temperatures in Figure 2. That this rise is not a consequence of a steady rise in the mean surface temperature, is shown by the record of temperature at eight-inch depth, also shown in Figure 3. From this record the annual mean temperature just below the surface is 4.0°F. It is interesting to note that an upward extrapolation of the straight line gradient (300 ft to 650 ft in Figure 2) intersects the surface very near this temperature.

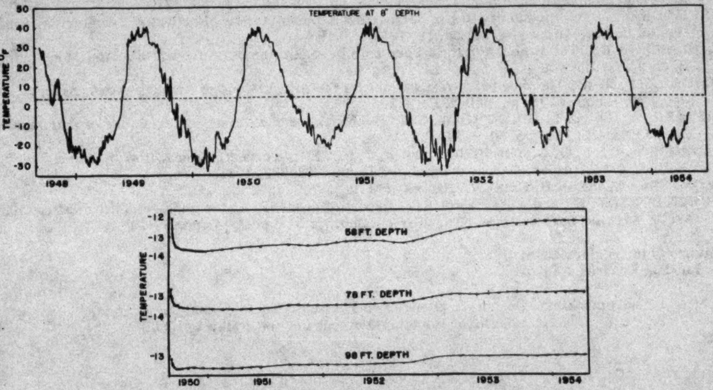

Fig. 3--(a) Annual variation of temperature just below surface;
(b) Rise of temperature 1950-1954 in region from 58 ft to 98 ft depth

It is not illogical to assume that the straight line connecting the mean annual surface temperature and the gradient at considerable depths represented the equilibrium gradient at some time in the recent past. For some reason, the region next to the surface layer has started to warm up with the result that a minimum appears in the temperature-depth curve and this minimum advances to greater depths with increasing times. If one cares to assume further that the heating has been at a reasonably uniform rate starting from some time at which the gradient was the extrapolation given above, it is found that for all depths between 50 ft and 100 ft the heating started during the autumn of 1948. This was two full years before the drilling of Hole 1 and five years before the drilling of Hole 20. A discussion of the probable causes of this heating must be very speculative until further information is available. The temperature records are being maintained and it is hoped they will indicate where the temperature-depth curve will stabilise itself.

Discussion--The thermal conductivity of the rock in this region does not appear to be abnormally high and hence the large heat flow must be attributed to the magnitude of the temperature gradient. As noted above, similarly large gradient have been observed at Barrow, Alaska [MacCARTHY 1952]. There are no published thermal conductivities to permit calculation of the heat flow at Barrow, but it is unlikely that these would differ by more than 25 pct from the values used here. If this should be the case, the heat flow at both Barrow and Resolute would be significantly greater than that observed elsewhere on the Earth's surface.

Acknowledgments--Grateful acknowledgment should be made to the U. S. Bureau of Mines for the provision and calibration of the thermistor elements used in this work. The later stages of deep drilling were financially assisted by the Division of Building Research, National Research Council, Ottawa, and the programme was thereby continued until a depth of 650 ft was successfully obtained.

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REPORT OF THE SPECIAL COMMITTEE ON COSMIC-TERRESTRIAL RELATIONSHIPS FOR THE YEAR ENDING JUNE 30, 1955

Harlan T. Stetson, Chairman
E. O. Hulburt, Vice Chairman

Ross Gunn
Serge A. Korff
Robert A. McMath
Donald H. Menzel
W. H. Thom, Jr.
Herbert Riehl
Harry W. Wells

The year 1954-1955 has been of special interest for its continued low solar and geomagnetic activity, facilitating certain investigations of interrelated phenomena. The Zurich monthly mean sunspot number reached a low of 0.2 in January and again in June 1954. With the new solar cycle, as indicated by the occurrence of spots at higher latitudes, sunspot numbers have been increasing, attaining a provisional value of 20.8 for February 1955. The suggestion is here made to observatories providing sunspot counts that separate sunspot numbers be issued for the old and the new cycle during the interval of overlap. This might afford a better basis for correlation with certain terrestrial phenomena.

Acknowledgment is here made of the prompt and effective service of the U. S. Naval Observatory in distributing solar data to those interested.

Helen W. Dodson reported for the McMath-Hulbert Observatory of the University of Michigan, under the Directorship of Robert R. McMath:

The program of basic solar research has been continued at the McMath-Hulbert Observatory. The high-dispersion vacuum spectrograph has been constructed, and initial tests indicate a working resolving power of about 600,000. The dispersion is 11 mm per angstrom in the seventh-order spectrum in the region of the K line.

Continuous monochromatic studies of solar features were continued through the minimum of the sunspot cycle. The development of a spot and plage between August 20 and 27, 1954, was recorded and has been studied photometrically. These measures permit interesting comparisons of this well defined solar phenomenon with concomitant solar activity and with terrestrial effects at a time when solar activity was relatively simple.

Photometric measurements of solar flares have been continued. These studies indicate that the position of the flare on the solar disk plays a role in the observed Hα phenomenon. There are center-to-limb variations in (1) the rates of increase and decrease in Hα intensity, (2) average maximum intensity, (3) duration of the flare, (4) width of Hα at maximum, and (5) the relative ending times of the Hα flare and the associated SID (sudden ionospheric disturbances).

Our photographic and photometric flare data have been compared with records of the variations in the strength of the WWV signal as recorded at Lake Angelus and at Ithaca, New York, on records kindly made available to us by Charles R. Burrows, Director of the School of Electrical Engineering. These intercomparisons have indicated that there are numerous flare-associated disturbances of the ionosphere that have not been reported as SID in the official records. Some of these fades are more gradual than the heretofore recognized Dellinger effect. Their reality has been confirmed by examination of the standard records at CRPL. This matter is being investigated further.

Charts containing solar, ionospheric, and geomagnetic data have been kept up to date. An instrument recording variations in the magnetic declination has been set up to supplement records from the total intensity variometer and the 5 Mc/sec WWV signal recorder.

Donald H. Menzel, Director of the Harvard College Observatory and cooperating stations, has done much to further interest in the field of solar-terrestrial relationships, and makes the following comments:

During the year, Harvard astronomers have attempted to integrate researches in the field of solar-terrestrial relationships. An informal organization known as the 'Solar Associates', has been formed, consisting of Donald H. Menzel, as chairman; Walter O. Roberts, Director of the High Altitude Observatory, Boulder and Climax, Colorado; John W. Evans, Superintendent of the Upper

Air Research Observatory, Sacramento Peak, Sunspot, New Mexico; Richard N. Thomas, Harvard College Observatory, Cambridge, Mass.; and Alan H. Shapley, Central Radio Propagation Laboratory, National Bureau of Standards, Boulder, Colorado. This organization was set up primarily to coordinate the work at the institutions above named. The primary responsibility for collecting the observational data and issuing it in usable form has been delegated to the High Altitude Observatory at Boulder. Their summaries of solar activity give not only the observations of the intensities of coronal lines, the location of disturbed regions on the Sun, and the occurrence of flares, but also give some forecast of the locations of disturbed solar areas.

The past year has been appreciable improvement and enlargement of the observing instruments at the Upper Air Research Observatory. Chief of these is the installation of the 16-inch coronagraph, and associated high-power spectrographs.

Despite the fact that the Sun has been extremely inactive during the past year, a certain amount of solar activity has occurred and we have obtained excellent records both of the coronal spectra and of the motions of prominences.

Working at Cambridge on the theoretical side, David Layzer, Max Krook, and D. H. Menzel have continued to develop theories of sunspots and solar prominences [FERRARO, 1955]. A study, now well under way, of the torsional oscillations that might exist in a stellar interior, in the presence of a magnetic field, clearly indicates the possibility of the formation of toroidal magnetic fields in the equatorial plane. The period of oscillation appears to be reasonably close to the observed 22 year sunspot cycle. Moreover, the fields reverse in successive halves of the cycle. We believe that these fields, amplified by the hydrogen convective zone, find their way to the surface and thus produce sunspots. We have further studied the phenomenon of magnetic buoyancy, and conclude that large masses of gas containing magnetic fields will tend to rise. The electric currents associated with these fields appear to be ample for explaining the general characteristics of prominences in the neighborhood of spots. Hence this new work appears to be a natural extension of the studies we have been making in recent years.

An investigation of the E layer of the ionosphere, carried out with the aid of computing machines, is now nearing completion. We hope, as a result of this study, to be able to predict the E layer critical frequencies for a given point on the Earth's surface, for a given day of the year, and for a given phase of the spot cycle. We expect that this work will eventually lead us to an ionospheric index of solar activity. We are currently extending our studies to the F-2 layer.

E. O. Hulburt of the Naval Research Laboratory reports that investigations there have included much of importance in the field of Cosmic Terrestrial Relationships and summarized the work as follows:

Radio astronomy--The radio emission from the Sun at wave lengths of 9.4 cm and 0.86 cm was measured during the total solar eclipse of June 30, 1954, in Sweden. The brightening of the solar limb at 9.4 cm was determined, and partially completed analysis indicated that the limb brightening at 0.86 cm was small and of the order of magnitude to be expected from theory. Radiation from the corona at 0.86 cm was found to be less than one per cent of that from the Sun. The 'surface' of the Sun for this wavelength was found to lie in the chromosphere, about 6000 km above the visible photosphere.

Photometric measurements of the solar corona, as photographed by the NRL expedition to Khartoum on February 25, 1952, were carried out and related to other measurements and theoretical studies. The removal of the F-corona and calculation of electron densities according to van de Hulst's model appears to give consistent results here. It has also been possible to compare the electron densities with the red and green coronal lines near the great streamer. An examination of the data shows a very close correlation with the emission lines.

Observations of the 21-cm radiation from the neutral hydrogen in the galaxy indicate the existence of a spiral structure. The velocities of approach of several portions of the galaxy have been determined. In addition to the previously known radiation at this wavelength, absorption has been demonstrated for several sources for the first time and this information has been integrated into the general picture. In particular, a distance of 3000 parsecs to a prominent radio source in the direction of Cassiopeia has been established.

In March 1954, a second survey of the sky was undertaken with the NRL 50-foot radio telescope at 9.4 cm wavelength. Radio emission from eleven bright H II regions was detected. It is likely that these are mostly thermal sources. In addition, the radiation at 9.4 cm from the radio source identified with the unusual galactic nebulosity IC443 was measured. A total of 24 discrete radio sources have now been detected at 9.4 cm with the NRL radio telescope. A survey has also been made at 3.15 cm (9500 Mc/s) of discrete radio sources, or radio 'stars,' principally those recently detected at a wavelength of 9.4 cm using the same 50-foot antenna. At this wavelength the antenna pencil beam has a width of about nine minutes of arc. Seven sources were detected: the Orion

Nebula and two other bright hydrogen emission nebulae, three bright sources known at meter wavelengths, and a source recently suggested as the nucleus of our Galaxy. These are the seven brightest sources observed at 9.4 cm. This is also the first radio detection of galactic or extra-galactic radiation at a wavelength shorter than 9.4 cm. The radiation intensity of the Orion Nebula measured at 3.15 cm appears to be consistent with the thermal model of this source derived from the 9.4 cm measurement.

Upper atmosphere--The ambient positive-ion composition of the upper atmosphere in the range 8 - 49 atomic mass units was measured between 93 and 219 km by means of a Bennett radiofrequency mass spectrometer carried in the Viking-10 rocket, May 7, 1954. The most prominent ion peaks found between 93 and 124 km on the ascent were at 16,26,30 and 32 AMU. Other less prominent peaks occurred at 12,18,19,23,38 and 45 AMU. From 124 to 219 km ions of 16 and 32 AMU persisted [JOHNSON and MEADOWS, 1955].

Measurements in the ionosphere using the Seddon propagation technique were conducted with the Viking-10 rocket launched at 10h 00m MST on May 7, 1954, at the White Sands Proving Ground, New Mexico. This rocket reached a record altitude of 219 km. Ordinary and extraordinary indices of refraction at 7.754 Mc were measured, and from these the electron distribution from 84 to 200 km were determined. By using the P′-f records taken during the rocket flight, the electron density was extrapolated up to the maximum of the F^2-region (2.9×10^5 el/cm^3 at 288 km).

The measurements showed a rapid increase in density from 10^4 el/cm^3 at 91 km to 10^5 el/cm^3 at 101 km. This was followed by additional but less rapid increases up to the peak of the F1 region (2.1×10^5 el/cm^3 at 170 km). Densities in the 170- to 200-km region were, in general, five to ten per cent lower than F1 maximum density. These latest results agree well with previous results reported. In all cases, the daytime ionosphere was found to remain dense throughout the E region and up to the F1 region, with only occasional minor peaks in density; the distribution obtained agreed very closely with the P′-f records. Sporadic echoes are apparently due to partial reflections from high gradient regions [SEDDEN, PACKER and JACKSON, 1954].

On October 4, 1954, an Aerobee rocket fired from the White Sands Proving Ground reached an altitude of 100 miles. Included in the rocket instrumentation was a 16 mm movie camera loaded with color film. Enlargements of the individual frames of this film have been assembled into a mosaic. This mosaic picture shows roughly two million square miles of the Earth's surface in its natural color. Included in the picture are the arms and the eye of a large cyclonic storm centered over Texas.

Solar radiation--On Feb. 21, 1955, a new ultraviolet spectrum of the disc of the Sun was obtained from a rocket at an altitude of 115 km [JOHNSON, MALITSON, PURCELL and TOUSEY, 1955]. About 30 emission lines are present covering the range 1808 to 977A. Strongest of these is Lyman α; Lyman β is present, but γ is not. The emission lines have all been identified and come from the following atoms: Si II, III, IV; C, I, II, III, IV; Al II; He II; O I, VI; N V. They must originate in the top of the chromosphere or bottom of the corona. The continuum was detected down to 1550 A, with Fraunhofer lines at least to 1680 A. Limb darkening was marked in the continuum, but the emission lines showed neither limb darkening nor brightening.

A value for the solar constant of 2.00 cal/min^2 sec was published [JOHNSON, 1954]. It is based on the work of the Smithsonian Institution, but with the infrared and ultraviolet corrections revised by means of new ultraviolet data from 3400 to 2200 A obtained from rockets and new measurements from Mount Lemmon, Arizona, in the range 3000 to 6000 A.

By means of photon counters on Aerobee rockets fired in November and December 1953, the following results were obtained: The normal solar x-ray spectrum contains about 0.1 erg/cm^2 sec between 10 and 100 A and resembles black-body emission at 800,000 deg K. A correlation was observed between variations in x-ray intensity and coronal activity in the red and green lines. The solar Lyman α line is less than 0.5 A wide under quiet conditions of the Sun. The intensity of solar radiation at 1450 A and 1300 A resembles black-body emission at 4050 deg K and 3900 deg K respectively. The molecular oxygen content was measured to 130 kms at which level less than 88 pct was dissociated. Air-density determinations made on the basic of absorption of monochromatic x-ray radiation were approximately 1/3 the Rocket Panel values at 110 to 130 km [FRIEDMAN, HAVENS, FRIEDMAN and HULBURT, 1954].

Audiofrequency atmospherics--Considerable data have been collected which tend to support Storey's recent theory on the mode of propagation of the common whistling atmospheric [STOREY, 1953]. However, unusual types of whistlers are frequently observed which, although associated with lightning discharges, do not follow the regular dispersion law. Supplemental theory will be required to explain the observed phenomena. Some of the more unusual types have a tendency to be more prevalent during times of magnetic disturbance, at which times the 'dawn chorus' is also usually present. Rates of occurrence, relative amplitudes, dispersions, frequency analyses, and other characteristics of these atmospherics are being compiled and correlated with other geophysical phenomena. Simultaneous observations are frequently made at the Naval Research Laboratory and Dartmouth College, and many whistlers have been recorded simultaneously at both locations. Although the 'dawn chorus' shows excellent correlation with the aurora and magnetic activity, the relative amplitude and character may vary considerably at places 500 miles apart.

Cosmic rays--In cosmic-ray exposures of stripped stacks of nuclear emulsions near the geomagnetic equator, 16 tracks of stopped K-mesons were investigated. Nine originated in stars, two are K-mesons, and two others are attributable to $K\mu_3$ or to the alternate mode of charged τ decay. One event is a rare example of a 'complete τ event,' that is, production, decay, and termination of all three pion secondaries within the emulsion block [SEEMAN, SHAPIRO, and STILLER, 1955]. An observation of the non-mesonic decay of a He^{4*} excited fragment incorporating a bound Λ° particle tends to confirm the suspected weak binding of a Λ° compared to that of a neutron. A comparative study of various ionization-range methods of mass determination, and development of an 'opacity' method suitable for short ranges is under way [O'DELL and SHAPIRO, 1955]. Evidence for the nuclear absorption of a fast, charged hyperon Y by a nucleon N with the emission of a K-meson suggests the occurrence of the reaction $Y + N \rightarrow N + N + K$ [BLOCK and KING, 1955]. Energy measurements on the secondaries of 61 electron tridents between 0.1 and 10 Bev yielded a mean free path for production of such tridents of 134 ± 42 cm in nuclear emulsion [BLOCK, KING, and WADA, 1954].

H. W. Wells of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington notes that the Institution has, as usual, investigated many phenomena and interrelationships, the subject matter of which is of interest to the work of the Committee. Much of this is given in detail in the Annual Report of the Director. Wells calls attention particularly to advances in the field of radio astronomy, as follows:

The quiescent period of the solar cycle has given opportunity for radio-emission studies over the entire disk of the Sun with minimum interference from disturbed solar conditions. The occultation of the Taurus region by the solar corona during the sunspot minimum for June, 1954, gave the opportunity for further investigation of radio scatter and refraction by the solar corona, which was found to extend further than would have been expected.

Perhaps the most striking new development to come from the Department was contained in the announcement of radio waves from the planet Jupiter, [BURKE and FRANKLIN, 1955]. It is believed that the sources of the planetary radio emission are from electrical storms in the atmosphere of the planet similar to those accompanying thunderstorms in the Earth's atmosphere.

The study of traveling disturbances, or ionospheric 'winds,' reported last year, has been continued, together with relations to radio star scintillations.

The increasing interest on changes in solar activity and then possible relation to meteorological effects has continued to claim the attention of many investigators. The new value of the solar constant, 2.00 cal/cm^2 min, reported last year as a result of new corrections to the Smithsonian values through high rocket investigations, appear to promise new progress in this field of research. Furthermore, during the year there has been published [ALDRICH and HOOVER, 1954] a revised study of solar data which show once again a correlation between solar radiation and sunspot activity.

Herbert Riehl of the University of Chicago group reports as follows;

Extraterrestrial influences on weather have continued to engage meteorological research attention along several fronts.

The Bowen hypothesis of rain stimulation from meteor showers has been a center of controversy and some adverse statistics have been published. According to one study, one of Bowen's principal rainfall singularities at Sydney is due to heavy rainfall associated with the anomalous passage of a single tropical cyclone along the Australian East Coast. Another report points out that increased rainfall about the middle of January may be related to a peak of disturbed weather activity about that date as measured by the meridional circulation index - the mean intensity of the north-south flow aloft averaged around the northern hemisphere. It is admitted however that the peak of this index itself remains to be explained. On the other had, special sampling of the air has been conducted at several locations last January with the object of obtaining a direct test of the hypothesis. Results of these samplings have not yet been published.

No further news on solar-terrestrial relations has come from the sources cited last year but a new attack on the problem by SHAPIRO [1954] appears interesting. He correlates variations in the geomagnetic K_p index with persistence of five-day mean 500-mb charts over North America for the period February 1953 to February 1954. He finds that major minima of persistence follow a rapid rise of K_p from a low level (75) to a high level (140). The minima lag the K_p rise by about ten days. Conversely, each rapid rise of K_p was followed by a significant drop of 500 mb persistence.

Shapiro notes that his sample is limited in time and proposes to extend his correlation over several years before drawing further conclusions. Presumably the area studied should also be increased. Shapiro mentions that due to the more regular variations of K_p at low compared to high sunspot numbers, the effect may be noted mainly during sunspot minima.

Finally it may be noted that a new calculation of the solar constant will aid in determining the heat balance of the atmosphere and the latitudinal heat fluxes necessary for maintaining this balance [JOHNSON, 1954].

It is of interest to note that Riehl will be associated with the High Altitude Observatory at Boulder, Colorado, during the summer of 1955, and will devote most of his attention to solar-atmospheric relations.

E. M. Brooks of the Institute of Technology, St. Louis University reports on a study of sunspots and atmospheric temperatures at St. Louis showing a small negative correlation between mean annual temperatures and the Wolf annual sunspot numbers. An analysis of available data of over 100 years have shown that the warmest and coolest temperatures occurred one year before sunspot minimum and one year after sunspot maximum respectively.

A separate harmonic analysis of mean temperature during each of the four seasons for the 11 and 5 1/2 year periods shows the same relationships to the sunspot cycle as does the annual temperature curve, with one exception. The first harmonic for autumn was out of phase with those of the other seasons and this phase changed from the 19th to the 20th century. The amplitude variations were consistent but small and of the order of 1° Fahrenheit [BROOKS, 1955].

S. A. Korff of New York University and Reporter on Cosmic Rays for the U. S. National Committee of the International Geophysical Year, describes the activities of his group as follows:

During the summer of 1954, we again occupied the Mt. Wrangell Observatory in Alaska. We operated the neutron equipment there. No spectacular fluctuations in the neutron intensity were observed.

During the same summer, we also made some balloon flights in northern Minnesota. In these flights we measured the neutron intensity up to altitudes of about 90,000 ft. The results of this work are now being prepared for publication. This set of flights completes our world survey of cosmic ray neutrons [NEUBURG, SOBERMAN, SWETNICK, and KORFF, 1955].

Contributing further to the field of Cosmic Terrestrial Relationships was a calculation of the effect of the melting of polar ice on the speed of the Earth's rotation, which led to the following conclusion 'Superimposed on semiannual fluctuations we have a long-time progressive change, which requires some 10^5 km^3 to melt to cause a change of one second per year. Indeed, only one or two tenths of a per cent of all the Earth's ice need melt to cause a one-second-per-year change in the length of the day' [KORFF, 1954].

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EXPEDITIONS OF THE M/V THEODORE N. GILL OFF THE SOUTH ATLANTIC COAST OF THE UNITED STATES, 1952-1954

W. W. Anderson and R. B. Abel

Abstract--The U. S. Navy Hydrographic Office, the Fish and Wildlife Service, and Office of Naval Research are jointly prosecuting a program of the oceanography of the offshore waters from Hatteras to Straits of Florida. A two-year program of bimonthly cruises has recently terminated. Measurements of physical and biological properties, chemical content, and meteorological conditions were carried out.

In 1949 the Woods Hole Oceanographic Institution and the U. S. Fish and Wildlife Service jointly inaugurated a comprehensive program of oceanographic and marine biological investigations in offshore waters as far south as North Carolina.

Early in 1952, the Fish and Wildlife Service, U. S. Navy Hydrographic Office, and the Office of Naval Research agreed to collaborate on an amplified extension of this program to include the area from Cape Hatteras to the Florida Straits and involve studies of chemical and biological conditions by the Fish and Wildlife Service in cooperation with the Georgia Game and Fish Commission and the Florida Board of Conservation (through the University of Miami), physical oceanography by the Hydrographic Office, and scattering-layer observations by the Office of Naval Research.

The Fish and Wildlife Service M/V Theodore N. Gill, was converted and outfitted for the work early in 1952. She has a length of 97 ft, beam 21.5 ft, draft 11.5 ft, displaces 187 tons, and has a cruising range of 3500 mi. She is equipped with CG Model RD-137 Loran, Navy Model SO-1 Radar, EDO AN/UQN/1B echo sounder, National Type CNA receiver, RCA transceiver Type CRM, and Sperry automatic pilot. Her basic oceanographic equipment includes BT winch, Markey hydrographic winch (electric-powered, with capacity of 5000 m of 5/32-in cable), and two-drum Stroudsburg trawling winch (hydraulic powered, with 1/4-in cable) for plankton tows. There are accommodations for a crew of ten and eight scientists.

The first cruise took place in July 1952. This initial effort was a cooperative Hydrographic Office-Office of Naval Research program involving: (1) sound velocity meter tests, (2) scattering layer observations; (3) and the first in a series of bimonthly 24-hr oceanographic stations, termed standard stations.

By the end of 1952, the Fish and Wildlife Service's South Atlantic Fishery Investigations had been activated, and the plan of operations was firmed up by the participants. The standard station would be carried out bimonthly in a location of Elbow Cay. The Fish and Wildlife Service established a pattern of 80 regular stations between Jupiter Light (Florida Straits) and Cape Hatteras extending in area to beyond the axis of the Gulf Stream, also to be occupied bimonthly. These were 20 mi apart on the east-west lines, which were, in turn, 40 mi apart in the north-south direction, with stations established inshore between some of the east-west lines. Additionally, the Hydrographic Office requested nine special stations farther out, to be occupied once each season.

The field work relative to this program was prosecuted for over two years, terminating in December 1954, after the completion of 13 cruises, the last nine of which were over the established station pattern from Cape Hatteras to the Florida Straits. Monthly, seasonal, and annual coverages of the area were thus attained. The scientific complement consisted at various times of three to five people from the Fish and Wildlife Service, three or four people from the Hydrographic Office, one from the Office of Naval Research, one or two from the Georgia Game and Fish Commission, and one from the Florida Board of Conservation. Occasionally, the staff was augmented by scientists from the Johns Hopkins University and the Universities of Michigan, Rhode Island, and Miami.

Included in the observational program were: serial observations of temperature, salinity, and dissolved oxygen; collections of water samples for organic and total phosphate, nitrate, protein, and carbohydrate determinations ashore; plankton tows, dip-net and trolling samples; bottom sampling with coring instruments and an orange-peel dredge; transparency measurements; the usual meteorological observations; and bathythermographic observations on all stations.

Samples destined for inorganic phosphate, nitrate, protein, and carbohydrate analysis ashore were quick-frozen aboard ship to deter biological activity. Drift bottles were released for the Woods Hole Oceanographic Institution on most of the near-shore stations on the last four cruises. The scattering layer was observed using several types of echo sounders of varying frequencies.

During all this period, the work requirements of the observational program resulted in but little accomplishment of data analysis. With the termination of the field phase and start of the analytical phase, it is anticipated that a series of publications will be forthcoming as a joint effort of all participants.

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REPORT OF THE COMMITTEE ON SNOW, 1954-1955

R. A. Work, Chairman

M. E. Baudendistel	Clyde E. Houston	Vincent J. Schaefer
Robert D. Elliott	Gordon J. H. Kidd	J. van de Erve
Eric Hinton	C. C. McDonald	C. C. Warnick

The following report has been prepared by the Committee from a questionnaire sent to individuals and agencies active in snow research.

M. E. Baudendistel (U. S. Forest Service, Portland, Oregon)--In Colorado, under supervision of B. C. Goodell, Fort Collins, Colorado, studies are under way in five watersheds where snow is the primary source of stream-flow. Logging is under way on two of the five watersheds and will be completed during 1955. Continued stream-flow comparisons will show the effect of timber removal on stream-flow, and indirectly, the effects on snow and accumulation and rate of melt. From one watershed the timber is being removed in a strip-wise pattern, strip widths varying from 66 to 396 ft, and strip directions ranging through 180°. Cut-over strips alternate with uncut strips. During years following the completion of cutting, measurements will be made to determine the effects of strip width and orientation on the accumulation, drifting and melting of snow.

In Idaho, under supervision of Charles A. Wellner, Spokane, Washington, soil moisture conditions are being studied in relation to snowmelt patterns by use of paired installations of fiberglass electrical units in conjuction with snow course measuring points.

In the Northeast, under supervision of Howard W. Lull, Upper Darby, Pennsylvania, analysis is being made of snow and frost-depth measurements collected twice weekly over a period of two winters. Data were secured in 15 to 20 land-use conditions at each of six locations scattered throughout the Northeast. The first objective is to determine for each location whether significant differences exist in snow accumulation and frost depth. Later the data will be analyzed to determine snowmelt and frost disappearance rates by land-use conditions. In New Hampshire, an exploratory study is under way to secure snow depth and water content on an experimental watershed where a watershed management research program is being developed. Results will be used to help design more detailed studies.

In the Northern Rocky Mountains, Paul Ingebo has prepared a short paper on An Instrument for Measurement of the Density of Plant Cover Over Snow Course Points. Some results will be presented on relationships which exist between snow accumulation and plant cover density as measured by this instrument. In cooperation with the U. S. Weather Bureau, pictures are being taken at selected points during the snowmelt period to document the retreat of the snowmelt line on selected slopes. Accumulative readings at certain back country standpipe snow and rain gages are being made also in cooperation with the Weather Bureau.

In Utah, under supervision of George W. Craddock, Ogden, Utah, monthly storage-gage snow records as part of the year-round precipitation record have been taken at elevations 4500 ft, 7000 ft, and 8600 ft on the Davis County Experimental Watershed near Farmington, Utah, and also at 6000 ft, 7000 ft, 8600 ft, and 10,000 ft in the Ephraim Creek watershed at the Great Basin Research Center, Ephraim, Utah. The storage-gage records have been supplemented by snow samples at the more elevated stations, as well as by regular snow course measurements.

In California, under supervision of E. A. Colman, Berkeley, California, work in snow research has been confined to planning for research in snowpack management which, it is hoped, will get under way soon. The land in which stream-flow is fed mainly from snowmelt has been mapped. About 12 million acres are in this category, and this area (12 pct of the area of the State) is the source of 51 pct of the State's average annual runoff. Particular interest is in the part of the snowpack zone that lies within the commercial timber belt, because it is there that management of snow (for improved or increased water yield) has the best possibilities. The area of this portion is about nine million acres; its runoff is estimated at 38 pct of the State's runoff, or some 27 million acre feet per year. Most of the commercial timber land in these nine million acres is still uncut, but logging is now moving upward within the area and eventually all but the reserved lands will be cut-over and converted into second-growth forests. Considering the large amount of runoff originating in this area and the fact that forests there will be cut-over, it is important to learn how forests there can be managed for snow control as well as timber production. Some preliminary analyses of snow data obtained in past years at the Central Sierra Snow Laboratory by the Corps of Engineers and the Weather Bureau have been made. Henry Anderson has found in these analyses that there are marked differences in snow accumulation and in melt rates between spots with different degrees of forest cover and shade. He concluded that forest stands with small openings held snow longer than either dense forests or large open areas. This conclusion is not new, of course, but as a result of his analysis there are some specific clues to kinds of research that would provide quantitative measures of the effectiveness of snow control under a number of forest stand conditions.

F. A. Strauss (California Division of Water Resources, Sacramento, California)--Aerial photographs of the snowpack on watersheds of the San Joaquin, Kings, Kaweah, Kern, Mono Lake, and Owen Lake Basins are being secured. With an adequate amount of data, evaluation of summer snowmelt characteristics will be attempted.

K. Butson (U. S. Weather Bureau, Portland, Oregon)--The Weather Bureau has continued the photographic snow cover observation program described by Butson [Proc., Western Snow Conference April 1953]. Data are now available for the 1952, 1953 and 1954 melt seasons, and will be collected during the 1955 melt season. Observations are being secured in the Flathead, Coeur d'Alene, Clearwater, and Payette River Basins.

Only preliminary analysis of the photographs has been accomplished to date. Snow cover percentages for about ten dates per year have been determined by placing a 10 × 10 per inch transparent grid overlay on the enlarged 620 photographs. By comparing the estimated snow cover on the photograph with other snow-cover data on the same dates (aerial photographs, climatological substation snow depth reports, snow surveys, and other historical data which ordinarily are not available on a daily or even a weekly basis), a relation between per cent of snow cover on the photograph and on the river basin has been approximated for the Flathead River, Montana. The estimated basin snow cover has been tested for its value as a parameter in a snowmelt forecasting procedure. Although the number of years of available record is small, results to date are somewhat encouraging.

A day-to-day melt season forecasting procedure was developed for the Payette Basin, Idaho. The entire seasonal hydrograph, above base flow, was reconstructed from temperature, snow cover, and rainfall data without reference to observed flows. The choice of the Payette Basin above Emmett, Idaho, was based on the relatively dense network of strategically located climatological substations and snow courses and frequency of available reports. Radiosonde temperatures provide the basis for most of the temperature parameter. Daily increments of total computed runoff from snowmelt and rainfall are divided into two components: surface and ground-water runoff. These are combined and routed to the Emmett gaging station with the electronic stream-flow routing analogue, using separate storage and lag characteristics. A paper by A. L. Zimmerman, Reconstitution of the Snowmelt Hydrograph in the Payette River Basin, will be published in the 1955 Proceedings of the Western Snow Conference.

D. M. Rockwood (Corps of Engineers, Portland, Oregon)--The Snow Investigation Unit is preparing a summary report on snow hydrology to be completed in 1956. Snow Investigation Research Note 25, Lysimeter Studies of Snowmelt, dated March 1, 1955, presents the analysis of the 1954 spring melt data on a lysimeter site in the Central Sierra Snow Laboratory. Radiation and condensation melts were independently determined from radiometer measurements and special moisture-exchange experiments. The residual melt was considered to be caused by convective heat transfer. Derived melt equations gave condensation melts approximately equal to Sverdrup's (1936) and convection melts one-third of Sverdrup's.

In Research Note 24, Analysis of February 1951 Rain on Snow in a Densely Forested Area, runoff resulting from rain on snow was studied. Another study was made of the storage capacity of snow over a basin during a rain storm.

Month-by-month water balances for the years 1946-47 through 1949-50 were computed for Skyland Creek, Upper Columbia Snow Laboratory, using methods as described in Research Note 22, Forecasting Seasonal Runoff by the Water-Balance Method.

Other studies and work include construction and preliminary testing of an electronic analogue for storage-type routing which permits variation in the time-of-storage constant during actual routing. A study of diurnal variation of albedo at Central Sierra Snow Laboratory for the spring of 1954 show that the snow had measurable specular reflection. In another study, melt rates at several Upper California Snow Laboratory snow courses showed that ablation rates for the same air temperature varied directly with exposure to solar radiation.

Phil E. Church (University of Washington, Seattle, Washington)--The Department of Meteorology and Climatology has been investigating the albedo of snow mainly from data on the reflectivity of the Lemon Creek Glacier in Alaska. K. Buettner and R. Hubley find that the albedo of snow, water, ice, and clouds vary strongly with the Sun's zenith distance, cloudiness, and the melting-freezing processes. Work is going on concerning explanation of these changes as well as their importance for the heat balance of surface, troposphere, and ozonosphere.

O. W. Monson (Montana State College, Bozeman, Montana)--Continual effort has been made to further develop a small, easily transported, over-snow vehicle. A machine just newly developed will provide transportation for two men and can be transported in a half-ton pickup truck.

V. J. Schaefer and G. J. Klein (The Munitalp Foundation, Schenectady, New York, and National Research Council, Ottawa, Canada, respectively)--An International Classification for Snow has been issued by the Commission on Snow and Ice of the International Association of Hydrology. A committee consisting of V. J. Schaefer, G. J. Klein, and M. R. de Quervain prepared a draft of the proposed classification and submitted it to the International Commission on Snow and Ice at Brussels in 1951. After receiving suggestions for improvements, a final draft was prepared and presented at the Rome meeting of the International Union Geodesy and Geophysics in 1954. It has now been presented to the World Meteorological Organisation through its Technical Commission on Aerology with the recommendation that it be given field trials. The publication in final form was greatly assisted by the National Research Council of Canada through the help of R. F. Legget, Chairman of its Committee on Soil and Snow Mechanics.

Lorne W. Gold (National Research Council, Ottawa, Canada)--The Snow and Ice Section of the Division of Building Research occupied new cold room facilities. In this cold room a project to study the mechanical properties of ice, its ultimate strength in tension and compression, relationships between stress and strain, and its plastic properties was initiated. Some very preliminary observations have been made concerning the mode of failure of ice under load and the dependence of this mode on the direction of freezing of the ice. In the field of snow and runoff the section has done little more than continue the snow-survey project reported last year. Some observations that were made during the 1953-54 winter on the strength of snow have been analyzed and the results of this work will probably be published shortly.

C. C. Warnick (University of Idaho, Moscow, Idaho)--During the year a new project was initiated on a study of rime ice and snow-capping on high altitude gages. These gages were installed in the Boise River basin.

R. A. Work (Soil Conservation Service, Portland, Oregon)--Soil Conservation Service personnel conducted extensive tests on two new designs of over-snow machines during the winter of 1954-55 in an effort to further the development of equipment for over-snow travel.

J. W. Marr (University of Colorado, Boulder, Colorado)--The Institute of Arctic and Alpine Research is continuing its research on the interactions of snow accumulation and vegetation on the Front Range. Snow measurements and several other environmental factors are being taken at eight stations.

Robert D. Elliott (North American Weather Consultants, Goleta, California)--Efforts towards increasing snowpack through cloud seeding are under way in many western watersheds. Indicated results to date have been encouraging enough to lead to the continuance of such programs. Prominent ones are, proceeding from North to South: (1) Southern Cascades project, sponsored by California-Oregon Power Company, has now completed its 4th year of snowpack seeding; (2) The Lake Almanor, Mokelumne-Stanislaus, and Bass Lake projects, sponsored by Pacific Gas and Electric Company, which has sponsored cloud seeding - snowpack programs in the Sierras for three years; (3) The Upper San Joaquin program sponsored by the Southern California Edison Company, which is just completing its fifth year of operation; (4) Bishop Cups area project, sponsored by California

Electric Power Co. is one of the earliest projects; it was started in 1948 and has continued on a varying scale, to date; (5) Salt and Verde Rivers project, conducted by the Salt River Valley Water Users Association, from 1947 to date; (6) Moving east, the South Platte Water Resources Development Corp. has sponsored snowpack increasing projects for four years in the South Platte watershed area.

In addition to the above, several relatively new snowpack projects have commenced in California, Utah, Idaho, and Wyoming, and British Columbia. It is expected that the wealth of data being systematically collected by these various projects will reveal in detail the true effectiveness of weather modification techniques under various types of meteorological situations.

R. W. Gerdel (Snow Ice and Permafrost Research Establishment, Corps of Engineers, U. S. Army, Wilmette, Illinois)--Extensive stratigraphic studies were made by SIPRE during the past year on the permanent snow pack which constitutes the upper layer of the Greenland Icecap. At a site about 200 miles east of Thule and at an elevation of 7000 ft a 100-ft vertical shaft was excavated and core drill used at the bottom of the shaft to collect snow samples to a depth of 165 ft. Even at that depth the density was less than that usually associated with glacier ice and considerable permeability was measured. Since the layers produced by winter and by summer deposited snow were readily identified and no melting occurred at this elevation, it was possible to determine the annual precipitation for this North Greenland area with an accuracy probably equal to that obtainable from any precipitation records for state side stations. The samples from the 165-ft level represented snow that fell during the Civil War.

A residual mass curve prepared from the pit study shows that there was a period of above normal precipitation in this area of Greenland from 1920 to 1932 with below normal occurring since 1933. It appears that such stratigraphic studies as these, made by SIPRE may help to explain some of the long shifts in circulation patterns and storm tracks.

At its Keweenaw Field Station near Houghton, Michigan, SIPRE has active research projects on the vehicular trafficability of a snow surface as influenced by meteorological phenomena and metamorphic processes in the snow. Other projects include studies on the drifting of snow in a manner analogues to the movement of sediments in streams, and on the attenuation of radiation by blowing snow during wind storms not accompanied by precipitation. The micrometeorological research program originally initiated at the Central Sierra Snow Laboratory in California was transferred and greatly expanded at the Keweenaw Field Station.

The entire micromet, solar radiation, and snow drifting program is being transferred to Greenland for the summer with all personnel and equipment including a 12-meter mast scheduled to be on the Icecap by June 20, 1955.

J. R. Riter (Project Investigations Division, Bureau of Reclamation, Denver, Colorado)--The Bureau of Reclamation as of March 1955, is not actively engaged in conducting field investigations of snow. As the work demands, we are making office computations of snowmelt in relation to the synthesis of design floods for spillway computations of proposed dams. We are also engaged in making a limited number of seasonal water-yield forecasts which use snow survey data among other factors and also in the derivation of day-to-day rate-of-runoff of snowmelt forecasts for specific operational requirements. The Bureau of Reclamation continues to assist the Soil Conservation Service in the financing of the Federal-State Cooperative Snow Survey System through the contribution of funds which are made available for transfer on a reimbursable basis.

Soil Conservation Service
Portland, Oregon

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NUMERICAL FILTERS FOR DISCRIMINATION AGAINST TIDAL PERIODICITIES

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Abstract--Tidal contributions to a sea-level record can be reduced by a large factor by taking special weighted averages of hourly values. In the residual record it is possible to recognize changes of as little as a few millimeters taking place in a few days. The method might be useful in other geophysical problems.

Introduction--Tides often present troublesome 'high-frequency noise' in the study of longer-period fluctuations of sea level or other geophysical phenomena. Two methods are generally used to combat this trouble: (1) subtracting the predicted tide, and (2) taking averages. The latter method, which is the one herein discussed, is found to have the following advantages: (1) a greater degree of tidal elimination can be achieved than by subtracting the tidal prediction based on standard methods, (2) the procedure is independent of geographical location, and (3) it is not limited to locations where the tidal constants are known. This method has the disadvantage that it eliminates non-tidal oscillations of high frequency, and it is therefore unsuitable for studying variations with periods close to those of the tides. The computational difficulties are probably of the same order for both methods.

In this paper we shall consider only the elimination of the diurnal and shorter-period tides from data that are in the form of tabulated hourly (mean solar) values. The usual averaging processes are the 'straight' (in contrast to 'weighted') 24-hourly and 25-hourly averages, to be referred to as the A_{24} and A_{25} filters. DOODSON and WARBURG [1941] give a considerably more effective filter consisting of a 39-hourly weighted average, which they call 'multipliers for mean sea level.' This will be referred to as filter B_{39}. This filter was developed by combining a number of simple filters, each of which discriminates strongly against one or more of the principal tidal constituents. By approximately the same method we have developed a filter using a 51 hourly weighted average, to be designated as C_{51}. Neither the B_{39} nor the C_{51} filter was developed by a systematic method. The systematic development described below led to a series of filters, $D_{15}, D_{17}, \ldots, D_{51}$. After our extensive computational effort we are more than ever impressed with the effectiveness of Doodson's simple scheme.

Response characteristics of weighted averages--Let y(t) represent the input data consisting of signal plus noise, Y(t) the filter output. The averaging process is to be carried out according to

$$Y(t) = \sum_{i=-N}^{N} w_i \, y(t-i) \qquad w_i = w_{-i} \quad \ldots\ldots\ldots\ldots \text{(1)}$$

where 2N + 1 represents the number of values summed for the average, and w_i are the 'weight factors.' Y (t) can be called 'mean sea level' in accordance with common terminology in oceanic tidal work. The arguments of Y and y are integers representing numbers of mean solar hours. The weight factors are normalized according to

$$\sum_{i=-N}^{N} w_i = 1 \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

in order to give unit response for a component of infinite period.

The process (Eq. 1) of converting y into Y is a convolution of discrete functions. It can be shown to be equivalent to multiplying every sinusoidal component of y by the filter response factor

$$F(n) = \sum_{i=-N}^{N} w_i \cos in \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

without changing its phase (see, for example, WOODWARD [1953]). The quantity n is the hourly speed and is equal to 2π divided by the period in hours.

According to (1) we are considering only averages carried out over an odd number of hourly values. This is not a serious restriction, as a relatively large number of hours must be taken into account in order to achieve a satisfactory filter. Of more importance is the restriction of taking a symmetrical weighting array with respect to past and future data. We thus retain only those filters that introduce no phase change in the sinusoidal components of y, and exclude a number of filters having otherwise desirable characteristics. Incidently, it is a general rule that only filters which take into account both past and future values have this property of no phase shift.

In the case of the filters A which have equal weight factors, F is given by the simpler expression

$$|F| = |M^{-1} \csc(n/2) \sin(Mn/2)| \quad \ldots\ldots\ldots\ldots (4)$$

where M represents the number of consecutive hourly values of y taken into the average.

Criteria for determining an optimum filter--It will be convenient to define the autocorrelation function of any function f(t), t = 1, 2, ..., by the relation

$$\psi_f(\tau) = \langle f(t)\, f(t-\tau) \rangle \quad \ldots\ldots\ldots\ldots (5)$$

where the symbol $\langle \ldots \rangle$ denotes the time average

$$\lim_{T \to \infty} (1/2\,T) \sum_{t=-T}^{T} \ldots \quad \ldots\ldots\ldots\ldots (6)$$

If two functions f(t) and g(t) are such that

$$\psi_{f+g}(\tau) = \psi_f(\tau) + \psi_g(\tau) \quad \ldots\ldots\ldots\ldots (7)$$

f and g are said to be uncorrelated.

Let us consider the input signal y to be composed of two parts

$$y(t) = s(t) + u(t) \quad \ldots\ldots\ldots\ldots (8)$$

s being the signal, and u the (unwanted) noise, which, for the time being, is not necessarily restricted to purely tidal noise. The corresponding quantities after filtering by (1) will be denoted by S and U, and it follows from the linear properties of transformation (1) that

$$Y(t) = S(t) + U(t) \quad \ldots\ldots\ldots\ldots (9)$$

The problem now is to find the 'best' possible values of w_i. The procedure is to some extent arbitrary. LEVINSON [1947] for example discusses the separation of signal and noise by minimizing the quantity

$$\langle [\,Y(t) - s(t)\,]^2 \rangle$$

with respect to each weight factor for weighted averages which consider only past data. In the particular case of the weighted average (1), Levinson's criterion leads to the relation

$$\sum_{i=1}^{N} w_i \left\{ \psi_y(k+i) - 2\psi_y(k) + \psi_y(k-i) \right\} + \psi_u(k) = 0 \quad \ldots\ldots (10)$$
$$k = 1, 2, \ldots, N$$

provided that the noise is uncorrelated to the signal. Eq. (10) together with (2) determines the values of w_i.

The above method requires preknowledge of the autocorrelation of both the signal and the noise. It is difficult for us even to guess what the autocorrelation of the signal might be, and we shall therefore develop a somewhat different scheme which requires only that we prescribe the autocorrelation of the noise.

Whereas in Levinson's scheme the weight factors are determined by the criterion that the mean sea level Y resemble as closely as possible the input signal s, here we shall require that the output noise U be as small as possible, retaining, of course, the condition of unit response for zero frequency. We thus require that

$$< [U (t)]^2 > \equiv \psi_U (o) = \sum_{i=-N}^{N} \sum_{j=-N}^{N} w_i w_j \psi_u (i - j) \quad \ldots\ldots\ldots (11)$$

be a minimum with respect to all the w_i. Instead of the Lagrangian multiplier technique, we shall employ the equivalent method of eliminating w_o by means of (2) and differentiating with respect to the remaining w_i. After some rearrangement this leads to

$$(1/4) (\partial/\partial w_k \psi_U)(o) = \psi_u (k) - \psi_u (o) + \sum_{i=1}^{N} w_i \left\{ 2\psi_u (o) - 2\psi_u (i) - 2\psi_u (k) + \psi_u (k + i) + \psi_u (k - i) \right\} = 0 \quad \ldots\ldots\ldots (12)$$

$$k = 1, 2, \ldots , N$$

again provided that the noise is uncorrelated to the signal. Eq. (12) together with (2) determines the values of w_i. First, however, we must specify the function $\psi_u (\tau)$ for all τ from 0 to 2N, its values for negative argument being equal to those for the corresponding positive arguments because of symmetry.

The autocorrelation of the tide--Let us denote the purely tidal noise by z (t). It is well known that the tide can be accurately represented by a finite series of the form

$$z (t) = \sum_j H_j \cos (n_j t + \epsilon_j) \quad \ldots\ldots\ldots (13)$$

The semi-harmonic development of Darwin [SCHUREMAN, 1941] is adequate for our purpose as it can be shown that the variation of Darwin's 'constants' is slow enough to be unimportant.

Sinusoidal functions are uncorrelated according to (7) if they have periods which are different one from another and do not 'alias' together. The autocorrelation of the tide z is thus found to be

$$\psi_z (\tau) = (1/2) \sum_j H_j^2 \cos n_j \tau \quad \ldots\ldots\ldots (14)$$

independent of the ϵ_j.

The only tidal elements that enter are the constituent amplitudes H_j and speeds n_j. The speeds have been precisely determined from astronomic observations and, being characteristic of each constituent, do not depend on geographic location. The amplitudes do depend on location, but fortunately the calculation for determining the weight factors is not critical with respect to these values.

Our calculations are based on these conditions: (1) the same emphasis is placed on the diurnal and semidiurnal tide as is given by the equilibrium theory, and (2) for each of these the amplitudes H_j are taken proportional to the values given by the equilibrium theory. It is an observed fact that marked deviations from the latter condition are rare.

The theoretical amplitudes are called 'constituent coefficients' and will be denoted by c_j. In accordance with the above remarks, H_j will be replaced by c_j in (14).

In addition there are 'shallow-water constituents,' which are not present in the equilibrium theory. These arise from the distortion inherent in nonlinear coupling between various constituents. Their relative amplitudes vary considerably from place to place. We have selected one constituent (centrally located periodwise) for each of the 3-diurnal, 4-diurnal, 6-diurnal and 8-diurnal species, and arbitrarily assigned them the amplitudes shown in Table 2. These are included in the computation of the autocorrelation of the tide according to (14).

Non-tidal noise--The autocorrelation of the high-frequency noise x is not as easy to prescribe, but it is not necessary to do so with great accuracy. A large part of x will consist of something which is uncorrelated from one hourly value to another, that is, random noise. This will arise from noise whose correlation time is less than an hour as well as from round-off in tabulating the values. With regard to the latter, it may be noted that the U. S. Coast and Geodetic Survey follows the practice of rounding off the hourly tidal heights to tenths of feet. Assuming that the errors from this

Table 1--Numerical filters for discrimination against tidal periodicities; the values shown except filters A, B, and C, have been determined by the minimization requirement (12);

Item	A_{24}	A_{25}	B_{30}	C_{51}	D_{15}	D_{15}^*	D_{17}	D_{19}	D_{21}	D_{23}	D_{23}^*	D_{25}	D_{27}	D_{29}
F_D	.0436	.0403	.00205	.000521	.0938	.0784	.0493	.0398	.0385	.0354	.0320	.0301	.0248	.0223
F_S	.0327	.0182	.000619	.000075	.0408	.0392	.0267	.0201	.0171	.0111	.0050	.00215	.00526	.00631
F_H	.0724	.0189	.00716	.0149	.779	.794	.277	.0169	.0206	.0220	.0385	.0134	.00171	.00486
F_R	.204	.200	.216	.163	1.36	5.53	2.62	.955	.377	.446	1.42	.511	.297	.237
F_2	.637	.610	.410	.355	.691	.683	.656	.638	.631	.617	.602	.592	.565	.552
KQ_1	-.0988	-.132	.0172	.0112	-.0654	-.0839	-.112	-.125	-.122	-.110	-.0960	-.0882	-.0661	-.0567
OO_1	-.0702	-.106	.00959	.00687	-.03	-.0462	-.08	-.09	-.10	-.083	-.0744	-.07	-.05	-.05
J_1	-.0377	-.0754	.00361	.00297	.01	-.0056	-.04	-.06	-.06	-.053	-.0494	-.05	-.04	-.03
K_1	-.00287	-.0426	.00015	.00016	.0544	.0363	-.0015	-.0221	-.0234	-.0225	-.0205	-.0199	-.0169	-.0154
S_1	.00000	-.0400	.00000	.00000	.06	.0395	.00	-.02	-.02	-.020	-.0182	-.02	-.02	-.01
P_1	.00287	-.0374	-.00013	-.00015	.0608	.0427	.0047	-.0163	-.0178	-.0174	-.0162	-.0157	-.0136	-.0124
M_1	.0347	-.0067	-.00029	-.00106	.10	.0800	.04	.02	.02	.012	.0110	.01	.01	.01
O_1	.0750	.0328	.00299	-.00001	.143	.126	.0846	.0605	.0565	.0515	.0464	.0429	.0345	.0311
Q_1	.117	.0743	.0104	.00395	.19	.172	.14	.10	.10	.092	.0842	.08	.07	.06
$2Q_1$	.162	.118	.0225	.0114	.226	.220	.177	.151	.145	.135	.125	.128	.100	.0923
KJ_2	.0206	.0588	.00355	-.00017	.0963	.102	.08	.0696	.0590	.0383	.0148	.0048	-.0211	-.0243
K_2	.00274	.0426	.00033	-.00001	.05	.0547	.04	.044	.04	.025	.0108	.005	-.012	-.014
S_2	.00000	.0400	.00000	.00000	.0424	.0476	.0449	.0403	.0348	.0227	.0100	.0044	-.0106	-.0128
L_2	-.00278	.0248	-.00107	-.00001	.00	.0084	.02	.019	.02	.010	.0052	.003	-.00382	-.005
M_2	-.0352	.0064	-.00058	-.00008	-.0380	-.0345	-.0183	-.00889	-.0069	-.00434	-.0019	-.0004	.00255	.0029
ν_2	-.0518	-.0102	.00130	-.00013	-.07	-.0698	-.04	-.032	-.04	-.018	-.0090	-.004	.007	.009
N_2	-.0545	-.0128	.00171	-.00013	-.0772	-.0748	-.0509	-.0354	-.0299	-.0204	-.0101	-.0051	.00729	.0095
μ_2	-.0713	-.0299	.00503	-.00014	-.10	-.107	-.08	-.0583	-.04	-.035	-.0183	-.009	.010	.013
$2N_2$	-.0739	-.0325	.00565	-.00006	-.113	-.112	-.0822	-.0618	-.0530	-.0372	-.0196	-.0111	.0103	.0145
M_3	.0354	-.00650	-.00909	.00312	1.18	1.14	.401	.00924	-.0316	-.0330	-.00399	-.0171	.00213	.00652
MS_4	-.0179	.0242	.00484	.00210	-.331	-.433	-.153	-.0186	.00313	.00983	-.0165	.00818	.00067	-.00174
$2MS_6$	-.0248	.0193	-.00361	-.000106	.182	.362	.169	.0125	-.0142	.000424	-.0280	.0160	.00302	-.00407
$2(MS)_8$	-.0201	.0265	-.00871	.0466	-.0849	-.474	-.0479	.0312	-.00391	-.00842	-.113	.0104	.00006	-.00282
									VALUES OF w_i					
i														
0		1/25	0	.032361	.25700	2.83272	.03628	-.03067	.14327	.02177	-.33726	-.15709	.01939	.09053
1		1/25	2/30	.035960	-.07287	-2.39448	.05204	.16228	.04063	-.00017	.07374	.03737	.03879	.04155
2		1/25	1/30	.035256	.04605	1.63989	.20557	.07198	-.04820	.06426	.24728	.19865	.06201	.00293
3		1/25	1/30	.036544	.32901	-.28444	-.05504	-.24712	.03424	.13701	.14321	.06263	.04875	.03760
4		1/25	2/30	.035556	-.17606	-.47744	-.42339	.07564	.09343	.01307	.00138	-.02159	.02349	.05276
5		1/25	0	.035360	-.07667	.70698	.47811	.33142	.06154	-.05324	-.30526	-.01674	.02600	.04803
6		1/25	1/30	.028350	-.42740	-1.06138	.62305	.04116	.03523	.05186	.30551	.00795	.04563	.04765
7		1/25	1/30	.028655	.74944	.95451	-1.31861	-.13933	.02881	.09211	-.11590	.12101	.05234	.02810
8		1/25	0	.023034			.92013	-.20854	.01044	.08861	.33525	.12065	.04949	.03104
9		1/25	2/30	.025733				.42785	-.02789	.02731	.11993	.00081	.04748	.04510
10		1/25	0	.028147					.20015	-.12570	-.58318	-.03555	.02161	.01729
11		1/25	1/30	.022330						.19398	.44667	-.08389	-.03576	.01120
12		1/25	1/30	.023839								.18724	-.03818	.01927
13			0	.017542									.14865	-.02009
14			1/30	.011113										.09232
15			0	.018324										
16			0	.016226										
17			1/30	.011218										
18			0	.019327										
19			1/30	.004512										
20				.003704										
21				.007513										
22				.004004										
23				.003808										
24				.007708										
25				.000104										

* See text under Example b.

Note: The weight factors are not given for filter A (the straight 24-hourly average), as this filter is not expressible in the form of (1). The signs given the values of F for filter A assume that the result Y is centrally located in time with respect to the hourly values of y going into the average. Thus for the average of the tidal heights for 0^h, 1^h, . . . , 23^h of any day, the result should be tagged with the time 11:30 of that day, and then there is 0 or 180° phase change, depending on whether F is positive or negative.

for the various tidal constituents are values of F, determined by (3); all the filters listed those marked with an asterisk were affected by an error in the computations

D_{31}	D_{33}	D_{35}	D_{37}	D_{39}	D_{41}	D_{43}	D_{45}	D_{47}	D^*_{47}	D_{49}	D^*_{49}	D_{51}
.0186	.00671	.00184	.000900	.000791	.000749	.000706	.000648	.000492	.00032	.000338	.00072	.000196
.00549	.00257	.000991	.000645	.000510	.000406	.000298	.000130	.000107	.00039	.000320	.00014	.000535
.00561	.00346	.00170	.000563	.000638	.000101	.000113	.000642	.000717	.000791	.0000645	.00155	.000290
.348	.365	.250	.190	.173	.168	.166	.164	.163	.184	.160	.342	.157
.518	.454	.420	.408	.401	.394	.389	.374	.352	.322	.325	.363	.292
-.0354	.00179	.0186	.0219	.0216	.0204	.0187	.0156	.0106	.00544	.00455	.0138	-.00167
-.0308	-.00306	.010	.0125	.0125	.0119	.0110	.00935	.00663	.00400	.00327	.00667	-.000216
-.0229	-.006	.008	.00477	.00499	.00485	.00454	.00392	.00290	.00212	.00162	.00393	.000276
-.0115	-.00445	-.00109	-.000204	.000005	.000071	.000090	.000105	.000114	.00031	.000120	.00035	.000100
-.010	-.004	-.001	-.0004	-.0003	-.0002	-.0002	-.0002	-.0001	.00019	.0000	.00014	.0001
-.00947	-.00401	-.00140	-.000692	-.00050	-.000425	-.000390	-.000304	-.000198	.00007	-.000080	-.00005	.000039
.00362	.000	-.002	-.00196	-.00196	-.00188	-.00178	-.00155	-.00120	-.00088	-.000753	-.00150	-.000278
.0230	.00924	.00195	.000199	-.00020	-.000316	-.000352	-.000354	-.000335	-.00078	-.000302	-.00090	-.000251
.0462	.0218	.010	.00674	.00580	.00531	.00493	.00468	.00335	.00135	.00216	.00284	.000899
.0735	.0396	.0229	.0181	.0166	.0155	.0146	.0130	.0105	.00625	.00737	.0103	.00397
-.0191	-.00461	.00263	.00409	.00371	.00298	.00213	.000739	-.00107	-.00282	-.00268	-.00077	-.00340
-.0120	-.00490	-.001	.000196	.0005	.000422	.000345	.000177	-.000055	-.00015	-.000301	.00012	-.000443
-.0110	-.00475	-.00125	-.000175	.00010	.000160	.000157	.000108	.000025	.00010	-.000075	.00019	-.000151
-.0050	-.00292	-.00175	-.00120	-.00088	-.000652	-.000445	-.000139	.000247	.00077	.000593	.00030	.000747
.00245	.00107	.00012	-.000096	-.00013	-.000130	-.000104	-.000054	.000020	.00006	.000086	-.00002	.000123
.0086	.0061	.004	.0028	.0022	.0016	.00114	.000443	-.0005	-.00186	-.00132	-.00051	-.002
.00940	.00678	.00442	.00331	.00257	.00197	.00141	.000560	-.000558	-.00200	-.00160	-.00059	-.00280
.0150	.0130	.009	.0081	.00636	.00500	.00365	.00158	-.00120	-.00466	-.00384	-.00111	-.00539
.0159	.0139	.0108	.00878	.00706	.00556	.00410	.00179	-.00130	-.00513	-.00424	-.00118	-.00897
.00784	.00525	.00197	.000663	.000142	-.000067	-.000120	-.000849	-.000017	.000164	.000076	-.0000786	.000117
-.00285	-.000987	.000093	.000426	.000241	.000051	-.000055	-.000091	-.000113	.000107	.000053	-.000134	.000423
-.00307	.00616	.00264	-.000622	-.000608	.000071	.000220	-.000099	-.00225	-.00242	.000057	-.00485	.000244
.00516	.00180	-.00253	.000540	.000242	-.000262	.000099	.000107	-.000216	.000521	.000065	.000706	.000121
.051993	.013027	.026644	.030100	.038886	.042787	.041362	.040769	.037652	.015520	.028190	-.027182	.023536
.061224	.037486	.026490	.036541	.039841	.040786	.041679	.039603	.034481	.045823	.030186	.099553	.027414
.022855	.062433	.051530	.044666	.040898	.039555	.039391	.035814	.032411	.022755	.033391	-.005821	.032803
-.008481	.041186	.068462	.048736	.041798	.038492	.033846	.032582	.034996	.027330	.035201	.029091	.034288
.087421	.027309	.033652	.048757	.041088	.032601	.031103	.033046	.035201	.039402	.035995	.042217	.034641
.087935	.052325	.025259	.031005	.029856	.028959	.031447	.033440	.033906	.047461	.034855	.048764	.033806
.022052	.060187	.041210	.009335	.017699	.029270	.031585	.032094	.033083	.039091	.032016	.065219	.031362
.024957	.010624	.004126	.012602	.021051	.026898	.030264	.031136	.030107	.002454	.029509	-.049745	.028991
.019676	-.038896	-.013264	.026400	.029890	.026253	.026944	.028236	.027623	.032050	.027048	.048229	.026667
-.021096	-.005750	.034358	.031519	.030450	.028444	.024263	.023333	.025209	.044621	.024648	.075983	.025217
.043198	.079748	.056975	.035942	.028109	.025794	.024209	.021245	.020207	.015036	.023259	-.008696	.025598
.103587	.102948	.049572	.035349	.026092	.022105	.022689	.021414	.019444	.011146	.021351	.005582	.022881
.035507	.042240	.040295	.024997	.022278	.021280	.019478	.021096	.022747	.022029	.019180	.023957	.018215
-.049158	-.026388	.003091	.015786	.018238	.018437	.019303	.020583	.020627	.023688	.019239	.024858	.018386
-.073666	-.066388	-.023191	.005583	.013181	.016707	.019609	.018708	.017039	.018995	.019727	.031414	.020009
.137992	-.043347	-.013248	-.002771	.010042	.017243	.016634	.016224	.017994	.013922	.018127	-.011496	.017322
	.157770	.002548	.005701	.012323	.013231	.013783	.015884	.017186	.033705	.015673	.081466	.013720
		.099815	.023685	.012502	.009528	.012450	.014485	.013431	-.011128	.012749	-.073496	.011578
			.051119	.013719	.011453	.010567	.009846	.010109	.016954	.009347	.051460	.009899
				.031793	.013325	.008751	.006272	.006724	.015602	.007117	.015233	.009243
					.018246	.008410	.004893	.003352	.003736	.005619	.008377	.008012
						.012996	.005897	.004955	-.006000	.004336	-.005213	.006001
							.013785	.008936	-.001480	.005119	-.041332	.005829
								.014408	.035047	.008139	.090334	.005349
										.014073	-.034357	.005647
												.015353

Table 2--Table of cos (in), i = 1, 2, . . .

Item	KQ_1	OO_1	J_1	K_1	S_1	P_1	M_1	O_1	Q_1	$2Q_1$	KJ_2
n	16.6834764	16.1391017	15.5854433	15.0410686	15.0000000	14.9589314	14.4966939	13.9430356	13.3986609	12.8542862	30.6265120
T	21.578	22.306	23.098	23.934	24.000	24.066	24.833	25.819	26.868	28.006	11.755
c	.0032	.0163	.0297	.5305	.0500	.1755	.0317	.3771	.0730	.0097	.0064
$\frac{1}{2}c^2$	.0000	.0002	.0004	.1407	.0012	.0154	.0005	.0711	.0026	.0000	.0000
i											
1	.95791	.96059	.96323	.96574	.96593	.96611	.96816	.97054	.97278	.97494	.86050
2	.83516	.84547	.85563	.86531	.86603	.86674	.87468	.88388	.89261	.90101	.48094
3	.64212	.66370	.68511	.70559	.70711	.70862	.72549	.74513	.76384	.78192	-.03251
4	.39500	.42963	.46419	.49752	.50000	.50248	.53011	.56248	.59349	.62365	-.53739
5	.11464	.16167	.20916	.25536	.25882	.26227	.30099	.34669	.39084	.43412	-.89206
6	-.17538	-.11901	-.06128	-.00429	0	.00429	.05288	.11046	.16691	.22281	-.99785
7	-.45063	-.39031	-.32718	-.26365	-.25882	-.25398	-.19897	-.13227	-.06612	.00035	-.82525
8	-.68796	-.63085	-.56905	-.50496	-.50000	-.49502	-.43796	-.36722	-.29552	-.22213	-.42243
9	-.86734	-.82167	-.76905	-.71166	-.70711	-.70253	-.64906	-.58053	-.50886	-.43349	.09826
10	-.97372	-.94772	-.91251	-.86959	-.86603	-.86242	-.81882	-.75962	-.69450	-.62310	.59152
11	-.99812	-.99907	-.98886	-.96794	-.96593	-.96385	-.93645	-.89395	-.84231	-.78149	.91977
12	-.93848	-.97168	-.99249	-.99996	-1.00000	-.99996	-.99445	-.97560	-.94428	-.90071	.99140
13	-.79984	-.86770	-.92314	-.96347	-.96593	-.96830	-.98913	-.99975	-.99485	-.97478	.78645
14	-.59385	-.69532	-.78590	-.86096	-.86603	-.87100	-.92082	-.96500	-.99126	-1.00000	.36310
15	-.33788	-.46813	-.59086	-.69946	-.70711	-.71467	-.79388	-.87338	-.93371	-.97610	-.16329
16	-.05345	-.20405	-.35238	-.49004	-.50000	-.50990	-.61639	-.73030	-.82532	-.90131	-.64311
17	.23546	.07611	-.08797	-.24703	-.25882	-.27057	-.39965	-.54417	-.67202	-.78236	-.94352
18	.50457	.35027	.18289	.01290	0	-.01290	-.15747	-.32596	-.48212	-.62419	-.98069
19	.73119	.59683	.44030	.27194	.25882	.24565	.09475	-.08858	-.26598	-.43474	-.74426
20	.89625	.79634	.66535	.51236	.50000	.48754	.34094	.15404	-.03537	-.22349	-.30021
21	.98586	.93309	.84145	.71766	.70711	.69639	.56541	.38758	.19718	-.00105	.22762
22	.99247	.99629	.95569	.87381	.86603	.85803	.75387	.59829	.41899	.22145	.69193
23	.91552	.98096	.99964	.97005	.96593	.96153	.89434	.77373	.61798	.43286	.96321
24	.76150	.88831	.97008	.99985	1.00000	.99985	.97786	.90358	.78335	.62256	.96576
25	.54336	.72564	.86918	.96113	.96593	.97041	.99911	.98019	.90606	.78105	.69888
26	.27949	.50578	.70436	.85656	.86603	.87519	.95674	.99903	.97945	.90040	.22702
27	-.00792	.24605	.48775	.69329	.70711	.72066	.85345	.95901	.99953	.97463	-.29097
28	-.29466	-.03307	.23528	.48252	.50000	.51728	.69582	.86247	.96519	1.00000	-.73777
29		-.30958	-.03452	.23869	.25882	.27884	.49388	.71511	.87831		
30		-.56169	-.30175	-.02150	0	.02150	.26049	.52561	.74361		
31		-.76953	-.54682	-.28021	-.25882	-.23730	.01051	.30513	.56845		
32		-.91672	-.75166	-.51973	-.50000	-.48001	-.24013	.06667	.36232		
33		-.99165	-.90123	-.72363	-.70711	-.69019	-.47549	-.17571	.13648		
34		-.98842	-.98452	-.87795	-.86603	-.85359	-.68057	-.40774	-.09678		
35		-.90727	-.99541	-.97211	-.96593	-.95913	-.84230	-.61574	-.32479		
36		-.75462	-.93310	-.99967	-1.00000	-.99967	-.95041	-.78746	-.53512		
37		-.54249	-.80218	-.95872	-.96593	-.97245	-.99800	-.91278	-.71630		
38		-.28759	-.61226	-.85208	-.86603	-.87932	-.98204	-.98430	-.85850		
39		-.01004	-.37732	-.68706	-.70711	-.72660	-.90355	-.99783	-.95397		
40		.26831	-.11463	-.47496	-.50000	-.52462	-.76752	-.95255	-.99750		
41		.52552	.15949	-.23032	-.25882	-.28709	-.58263	-.85114	-.98673		
42		.74130	.41611	.03010	0	-.03010	-.36063	-.69958	-.92224		
43		.89865	.64511	.28846	.25882	.22893	-.11567	-.50677	-.80756		
44		.98517	.82669	.52706	.50000	.47244	.13667	-.28412	-.64890		
45		.99404	.94746	.72954	.70711	.68394	.38028	-.04472	-.45492		
46		.92455	.99856	.88204	.86603	.84907	.59969	.19732	-.23619		
47		.78220	.97624	.97409	.96593	.95666	.78092	.42772	-.00459		
48		.57819	.88212	.99941	1.00000	.99941	.91241	.63292	.22726		
49		.32860	.72312	.95624	.96593	.97442	.98582	.80083	.44673		
50		.05312	.51096	.84756	.86603	.88338	.99644	.92154	.64189		

source are uniformly distributed from +0.05 to -0.05 feet, this introduces a random noise with a standard error σ of 0.88 cm.

Let σ_x represent the standard error of the random noise and σ_X the corresponding quantity after filtering. It can be shown that the filter response factor for random errors is given by

$$F_R^2 \equiv (\sigma_X/\sigma_x)^2 = \sum_{i=-N}^{N} w_i^2 \quad \ldots\ldots\ldots\ldots\ldots (15)$$

If all the 2N + 1 weight factors are equal and satisfy (2), then (15) reduces to the familiar relation

$$F_R = (2N + 1)^{-0.5}$$

for the tidal constituents

K_2	S_2	L_2	M_2	ν_2	N_2	μ_2	$2N_2$	M_3	MS_4	$2MS_6$	$2(MS)_8$
30.0821373	30.0000000	29.5284789	28.9841042	28.5125831	28.4397295	27.9682084	27.8953548	43.4761563	58.9841042	87.9682084	117.9682084
11.967	12.000	12.192	12.421	12.626	12.658	12.872	12.905	8.280	6.103	4.093	3.052
.1151	.4227	.0251	.9085	.0541	.1759	.0219	.0235	.1000	.1000	.0500	.0500
.0066	.0894	.0003	.4127	.0006	.0154	.0002	.0003	.0050	.0050	.0012	.0012
.86531	.86603	.87011	.87475	.87871	.87932	.86321	.88381	.72566	.51528	.03546	-.46896
.49752	.50000	.51419	.53039	.54427	.54641	.56012	.56221	.05317	-.46898	-.99749	-.56012
-.00429	0	.02469	.05317	.07780	.08161	.10618	.10998	-.64849	-.99859	-.10618	.99435
-.50496	-.50000	-.47123	-.43737	-.40753	-.40289	-.37255	-.36782	-.99435	-.56012	.98996	-.37255
-.86969	-.86603	-.84472	-.81836	-.79402	-.79014	-.76426	-.76015	-.79462	.42137	.17638	-.64491
-.99996	-1.00000	-.99678	-.99435	-.98789	-.98668	-.97745	-.97581	-.15890	.99435	-.97745	.97745
-.86096	-.86603	-.89338	-.92126	-.94213	-.94507	-.96233	-.96471	.56400	.60336	-.24570	-.27189
-.49004	-.50000	-.55589	-.61741	-.66782	-.67536	-.72241	-.72941	.97745	-.37255	.96003	-.72241
.01290	0	-.07400	-.15890	-.23153	-.24263	-.31376	-.32461	.85459	-.98729	.31376	.94950
.51236	.50000	.42712	.33941	.26094	.24864	.16818	.15564	.26283	-.64491	-.93778	-.16818
.87381	.86603	.81728	.75270	.69010	.67992	.61084	.59971	-.47314	.32268	-.38026	-.79176
.99985	1.00000	.99513	.97745	.95187	.94708	.91082	.90441	-.94950	.97745	.91082	.91082
.85656	.86603	.91447	.95725	.98273	.98566	.99804	.99894	-.90480	.68464	.44484	-.06256
.48252	.50000	.59634	.69745	.77521	.78634	.85214	.86132	-.36380	-.27189	-.87927	-.85214
-.02150	0	.12313	.26283	.37963	.39721	.50719	.52354	.37890	-.98484	-.50719	.86183
-.51973	-.50000	-.36197	-.23762	-.10802	-.08776	.04378	.06408	.91082	-.72241	.84331	.04378
-.87795	-.86603	-.78784	-.67854	-.56948	-.55157	-.42988	-.41026	.94498	.22036	.56698	-.90289
-.99967	-1.00000	-.98906	-.94950	-.89279	-.88225	-.80311	-.78926	.46065	.94950	-.80311	.80311
-.85306	-.86603	-.93332	-.98262	-.99954	-.99998	-.98675	-.98484	-.27643	.75816	-.62393	.14960
-.47496	-.50000	-.63514	-.76960	-.86382	-.87635	-.94343	-.95156	-.86183	-.16818	.75886	-.94343
.03010	0	-.17196	-.36380	-.51856	-.54121	-.67775	-.69714	-.97437	-.93148	.67775	.73529
.52706	.50000	.33590	.13312	-.04751	-.07543	-.25374	-.28070	-.55230	-.79176	-.71081	.25374
.88204	.86603	.75648	.59670	.43506	.40855	.22952	.20096	.17282	.11553	-.72814	-.97330
.99941	1.00000	.98056	.91082	.81210	.79393	.65918	.63593	.80311	.91082	.65918	.65918
.84756	.86603	.94991	.99677	.99215	.98767	.93486	.92310	.99275	.82311	.77489	.35503
.46737	.50000	.67250	.83305	.93152	.94303	.99217	.99576	.63769	-.06256	-.60422	-.99217
-.03870	0	.22037	.46065	.64492	.67078	.81773	.83700	-.06725	-.88758	-.81773	.57560
-.53436	-.50000	-.29898	-.02714	.20190	.23663	.45228	.48374	-.73529	-.85214	.54625	.45228
-.88606	-.86603	-.72328	-.50812	-.29012	-.25464	-.01881	.01806	-.99990	.00941	.85647	-.99982
-.99908	-1.00000	-.96968	-.86183	-.71174	-.68445	-.48551	-.45183	-.71588	.86183	-.48551	.48551
-.84296	-.86603	-.98417	-.99966	-.96073	-.94905	-.83880	-.81670	-.03907	.87876	-.89090	.54443
-.45977	-.50000	-.70820	-.88708	-.97666	-.98459	-.99617	-.99179	.65918	.04378	.42235	-.99617
.04730	0	-.26625	-.55230	-.75568	-.78249	-.92084	-.93638	.99575	-.83364	.92084	.38994
.54161	.50000	.24136	-.07916	-.35138	-.39152	-.63042	-.66338	.78598	-.90289	-.35705	.63042
.89001	.86603	.68831	.41380	.13814	.09395	-.19274	-.23621	.14496	-.09682	-.94616	-.98125
.99867	1.00000	.95643	.80311	.59416	.55673	.28997	.24587	-.57560	.80311	.28997	.28997
.83830	.86603	.97609	.99124	.90606	.88515	.70493	.67079	-.98033	.92447	.96673	.70928
.45211	.50000	.74219	.93106	.99816	.99992	.95524	.93963	-.84718	.14960	-.22141	-.95524
-.05587	0	.31547	.63769	.84813	.87336	.98242	.99046	-.24920	-.77029	-.98242	.18670
-.54880	-.50000	-.19319	.18457	.49238	.53699	.78012	.81092	.48551	-.94343	.15174	.78012
-.89390	-.86603	-.65167	-.31479	.01717	.06925	.39659	.44291	.95383	-.20197	.99318	-.91843
-.99819	-1.00000	-.94086	-.73529	-.46218	-.41420	-.08133	-.02801	.89880	.73529	-.08133	.08133
-.83358	-.86603	-.98863	-.97162	-.82944	-.79767	-.53926	-.49242	.35062	.95973	-.99894	.84214
-.44442	-.50000	-.77436	-.96455	-.99549	-.98862	-.87122	-.84241	-.38994	.25374	.01049	-.87122
.06446	0	-.36193	-.71588	-.92005	-.94095	-.99969	-.99662	-.91855	-.69823	.99969	-.02497
.55696	.50000	.14453	-.28788	-.62144	-.66617	-.89464	-.91923	-.94027	-.97330	.08039	.89464
.89772	.86603	.61344	.21223	-.17206	-.23061	-.58062	-.62821	-.44809	-.30481	-.99541	-.81418
.99763	1.00000	.92299	.65918	.31903	.26062	-.13098	-.19120	.28997	.65918	-.13098	-.13098
.82879	.86603	.99277	.94100	.73274	.68895	.34926	.29023	.86891	.96413	.98612	.93703
.43669	.50000	.80465	.98712	.94871	.95098	.74791	.70424	.97110	.35503	.20091	-.74791

The autocorrelation of random errors is given by

$$\begin{aligned} \psi_x(\tau) &= \sigma_x^2 \qquad \tau = 0 \\ &= 0 \qquad \tau = 1, 2, \ldots \end{aligned} \qquad \text{.............. (16)}$$

and the complete autocorrelation of the noise (tidal plus random) is then

$$\psi_u(\tau) = (1/2) \sum_j c_j^2 \cos n_j \tau + \psi_x(\tau) \qquad \text{.............. (17)}$$

x being uncorrelated to z.

Table 3--Table of $\psi_u(\tau)$ for the diurnal constituents, the semi-diurnal constituents, the shallow-water constituents, random errors, and the total noise, respectively; the latter is plotted in Figure 1

τ	Diurnal	Semi-Diurnal	Higher Species	Random Errors	Total Noise
0	.232100	.525500	.012400	.000240	.770240
1	.224513	.458915	.005684	0	.689112
2	.202249	.276052	-.003948	0	.474353
3	.166772	.023280	-.007170	0	.182882
4	.120411	-.235311	-.007031	0	-.121931
5	.066211	-.434178	-.002428	0	-.370395
6	.007728	-.522943	.004177	0	-.511038
7	-.051202	-.479179	.005216	0	-.525165
8	-.106721	-.314071	.003310	0	-.417482
9	-.155193	-.069551	.000852	0	-.223892
10	-.193450	.192350	-.003238	0	-.004338
11	-.219005	.405262	-.002159	0	.184098
12	-.230203	.515301	.002326	0	.287424
13	-.226337	.494717	-.000643	0	.267737
14	-.207692	.348905	-.005256	0	.135957
15	-.175520	.114968	-.002514	0	-.063066
16	-.131961	-.147699	.002007	0	-.277653
17	-.079892	-.372532	.005424	0	-.447000
18	-.022750	-.502673	.007051	0	-.518372
19	.035709	-.505347	.001839	0	-.467799
20	.091653	-.380127	-.005372	0	-.293846
21	.141423	-.158984	-.007834	0	-.025395
22	.181784	.101893	-.007269	0	.276408
23	.210116	.336388	-.000600	0	.545904
24	.224612	.485222	.010152	0	.719986
25	.224374	.510938	.010435	0	.745747
26	.209474	.407365	.000960	0	.617799
27	.180948	.201053	-.005065	0	.376936
28	.140723	-.055513	-.006739	0	.078471
29	.091488	-.297283	-.005124	0	-.210919
30	.036508	-.463162	.000730	0	-.425924
31	-.020585	-.511440	.003783	0	-.528242
32	-.076040	-.430290	.002826	0	-.503504
33	-.126227	-.240671	.002383	0	-.364515
34	-.167886	.009112	-.000257	0	-.159031
35	-.198330	.255699	-.002072	0	.055297
36	-.215628	.436784	.001833	0	.222989
37	-.218716	.506851	.001732	0	.289867
38	-.207478	.448634	-.004900	0	.236256
39	-.182738	.277353	-.006052	0	.088563
40	-.146202	.036741	-.001171	0	-.110632
41	-.100343	-.212143	.003849	0	-.308637
42	-.048232	-.406405	.008170	0	-.446467
43	.006671	-.497245	.006364	0	-.484210
44	.060741	-.462184	-.001714	0	-.403157
45	.110433	-.310668	-.006904	0	-.207139
46	.152517	-.081482	-.008422	0	.062613
47	.184282	.167160	-.005936	0	.345506
48	.203724	.372426	.004431	0	.580581
49	.209657	.482748	.011573	0	.703978
50	.201799	.470795	.005974	0	.678568

We must now choose a value for σ_x consistent with the relative importance we wish to place on the suppression of random errors and of tide. If we suppose that the tidal range is eight feet and the standard error 0.05 ft, we find that

$$\sigma_x^2 / \psi_z(o) \simeq 0.0003$$

According to Table 1, $\psi_z(o) = 0.77$ and hence $\sigma_x^2 \simeq 0.00024$. This value has been used in the computations.

Computations--The function $\psi_u(\tau)$ is plotted in Figure 1. It includes the separate effects of the diurnal, semi-diurnal, and shallow-water constituents, and of random errors. The constants entering (17) are given in Table 2 and the separate contributions from the three tidal species are given in Table 3. The value of $c^2/2$ was taken to be zero in some cases where its actual computed value was very small. This was done for three of the constituents listed in Table 2 and for all others not listed. In all, eight diurnal, eight semi-diurnal and four higher-species tidal constituents went into the computation of ψ_z.

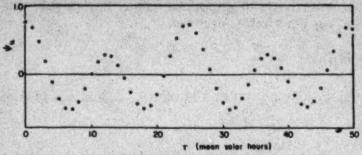

Fig. 1--Plot of the autocorrelation function $\psi_u(\tau)$ of the noise which is minimized in determining the weight factors

Having now specified the function ψ_u, the coefficients to (12) can be evaluated and w_i determined. These equations comprise a linear algebraic system of N equations in N unknowns. It is obvious that the larger the value of N the more effectively the minimization of $\psi_U(o)$ can be carried out. Let us consider $\psi_U(o)$ to be a function of N denoted by $\psi_U(o)_N$, and hypothetically determine the set of w_i for the case N equal to a certain value N_o. By (11), $\psi_U(o)_{N_o}$ can be evaluated. Let us now consider the set of w_i determined by letting $N = N_o + 1$. If the w_i determined in this latter case were exactly the same as in the previous case for $i = 1, 2, \ldots, N_o$, with $w_{N_o+1} = 0$, we would obtain the relation

$$\psi_U(o)_{No} = \psi_U(o)_{No+1}$$

However, since the determination of w_i is a minimizing process, its value must be equal to or less than its value for any particular arbitrarily chosen set of w_i. Therefore, we have the relation

$$\psi_U(o)_{N+1} \leq \psi_U(o)_N \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (18)$$

Once it is decided for which value of N the solution of (12) is to be carried out, the determination of w_i for all lesser values of N can be made without additional labor by using the elimination method of solving the linear algebraic equations. The maximum N value actually used was 25, necessitating the computation of the function up to the value $\tau = 50$. The result of this is to give sets of weight factors for all values of N equal to or less than 25, which correspond to weighted averages taking into account 51, 49, 47, . . . , consecutive values of y. The filters corresponding to $N \leq 6$ are not of much practical interest and are not given. The computations were performed on IBM automatic computers.

After the computations were done, it was found that the condition (18) was violated at one stage, indicating that a numerical error had crept in. The error was found to be a small discrepancy in the value of cos (8n) for the constituent P_1, an identical error having been made independently by two persons. After this error was corrected, solutions were obtained which satisfied (18) at all stages, and which also gave lower values of the quantity $\psi_U(o)_N$ for all N than the previous wrong solution. For the most part, however, the correct solutions are surprisingly little more effective than the corresponding wrong solutions although the corresponding sets of w_i differ considerably.

Results--Table 1 gives the weight factors and characteristics of all the filters that have been discussed.

The first row gives the filter factor, F_D, of the composite diurnal tide, defined as

$$F_D = \left\{ \Sigma_j \; F^2(n_j) \; c_j^2 \; / \; \Sigma_j \; c_j^2 \right\}^{0.5} \quad \ldots\ldots\ldots\ldots\ldots (19)$$

taking into account only the diurnal constituents. In the same manner F_S and F_H denote the filter factors for the composite semi-diurnal tide and for the composite higher-species tide. These quantities were computed on the basis of the constituents listed in Table 2. F_R is the filter factor for random errors according to (15), and F_2 is the filter factor for a component whose period is two days.

The mean square noise output for any given situation can then be approximated by

$$\psi_U(o) = (1/2)F_D^2 \sum_D H_j^2 + (1/2)F_S^2 \sum_S H_j^2 + (1/2)F_H^2 \sum_H H_j^2 + F_R^2\,\sigma_x^2 \qquad (20)$$

according to the above definitions. The success of the approximation depends on the tidal constituents of a species having amplitudes proportional to their equilibrium values. For this reason the third term of (20) is greatly in doubt. If the shallow-water tide is important and it is desirable to obtain a better estimate to $\psi_U(o)$, the third term of (20) should be replaced by

$$(1/2) \sum_H F^2\,(n_j)\,H_j^2$$

The response factor for the filters D_{21}, B_{39} and C_{51} is shown in Figures 2, 3, and 4. This is essentially (3) plotted against period instead of speed, n.

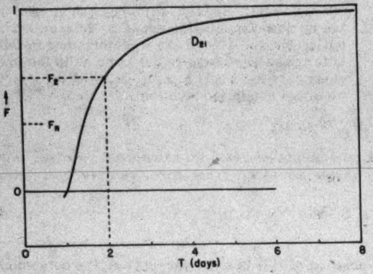

Fig. 2--Plot of F(T) for the filter D_{21}

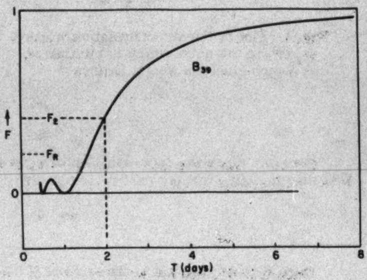

Fig. 3--Plot of F(T) for the filter B_{39}

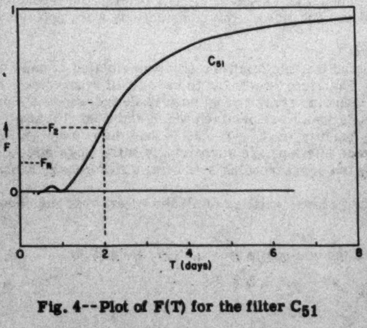

Fig. 4--Plot of F(T) for the filter C_{51}

The following examples illustrate the selection and use of the filters for any particular problem:

Example a--A tide gauge was established at station A and only 28 consecutive hourly tidal values were obtained before a storm washed out the installation. It is desired to obtain the best possible estimate of mean sea level (eliminating tidal effect) during that time. The tide at station A is known to be predominantly semi-diurnal, having a mean range of about five feet, with the diurnal tide contributing only about one foot. The quantity of data restricts us to a filter using 28 or less ordinates, that is, one which has a subscript of 28 or less. We shall first select the filter that has the smallest possible filter factor, F_S, for the predominant semi-diurnal tide. According to Table 1, this is D_{25}, for which $F_S = 0.00215$. The maximum residue of the semi-diurnal and diurnal tides are (0.00215)5′ = 0.3 cm, and (0.0301)1′ = 0.9 cm respectively, the diurnal residue being the larger. One might think that filter D_{27} would be better since it cuts down the diurnal tide more than D_{25}. For D_{27} we obtain for the maximum residue of the semi-diurnal and diurnal tides, respectively, (0.00526)5′ = 0.8 cm and (0.0248)1′ = 0.8 cm. Evidently the use of filter D_{25} will give a lower total residue. If random errors or the shallow-water tides give an appreciable residue, then they should be taken into account.

Example b--A sea-level study is to be made at station B, where the root mean square values of the diurnal and semi-diurnal tides $(0.5\,\Sigma\, H_j^2)^{0.5}$ are known to be one meter and two meters, respectively. The hourly tidal heights have been rounded off to tenths of feet giving rise to a standard error of 0.88 cm. Other random errors and the shallow-water tides are negligible. We wish to use the 'shortest' possible filter that will satisfy the requirement that the residual output of the tide (diurnal and higher) plus random errors have a rms value, r, of less than 2 mm. Hence

$$r^2 \equiv (1/2)[(100\,\mathrm{cm})^2\, F_D^2 + (200\,\mathrm{cm})^2\, F_S^2] + (0.88\,\mathrm{cm})^2\, F_R^2 \leq 0.04\,\mathrm{cm}^2$$

The values of r^2 for various filters are shown in Table 4.

Table 4--Values of r^2 for various filters

Filter	r^2 (cm^2)
D33	0.460
D35	0.085
D37	0.040
D39	0.031
B39	0.065
D41	0.028
D43	0.026
D45	0.023
D47	0.022
D*47	0.030
D49	0.022
D*49	0.094
D51	0.025

The filter D_{37} thus satisfies our requirements. For shorter filters the residual noise rapidly increases. If instead we had wanted to reduce the residual noise as much as possible regardless of the expense, then D_{47} would have been our choice.

Two considerations make it desirable to use the shortest filter satisfying the requirements of the problem: (1) computational labor, and (2) the filter's attenuation of that portion of the spectrum which we want to study. The value of F_2 is a useful guide in the latter consideration, as it is an index of the filter's response to periodicities just longer than those of the diurnal tide.

Table 1 indicates that the value of F_2 generally decreases with the length of filter. The reason for this is clear. For the D series of filters the minimization process was carried out without regard to the F_2 value, and the longer filters have a tendency to average out (attenuate) longer periodicities. Even for the worst case, however, the value of F_2 is sufficiently large to indicate that variations having periods of as little as two days can be satisfactorily studied with the filter.

Since the D filters were determined by minimizing an expression like (20), we should expect that $\psi_U(o)$ decreases with N but not that the magnitude of the individual terms of (20) decreases with N. In fact they do not. For this reason some of the filters determined using the numerical error actually have better values of one or more of the quantities F_D, F_S, or F_R than the corresponding 'correct' filters. Four of these are thought to be of possible use and are included in Table 1 marked with an asterisk.

It has been noticed that for filters larger than D_{35} the noise is largely due to random errors, and any subsequent improvement is essentially a $\sqrt{2N+1}$ reduction of these errors. This indicates that in order to reduce the residual noise even further it might be necessary to collect more accurate data. A better filter could then be obtained by placing less emphasis on the random errors.

With regard to the comparative effectiveness of the filters determined by the minimization criterion and those not, it is seen that the former are in every case superior, as was to be expected, to the filters A, B, C, and D* if the comparison is made between filters taking the same number of y values into the average.

Acknowledgments--The author would like to express his thanks to Walter Munk for his advice and encouragement of this study, to Carl Eckart for his advice and suggestions, to Robert Arenz and Dorothy Shumway of the U. S. Navy Electronics Laboratory at San Diego for solving numerically the set of linear algebraic equations with their IBM automatic computing machines, and to Margaret DeSelle and Janet Osborn for their help with the manual computations. This paper represents in part results of research carried out by the University of California under contract with the Office of Naval Research.

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open for formal discussion until May 1, 1956.)

Transactions, American Geophysical Union Volume 36, Number 6 December 1955

LETTER TO THE EDITOR

RELIABILITY OF AREAL MEAN RAINFALL ESTIMATES

Reliability of sample mean rainfall estimates for data from 198 summer storms for a 20-gage network within a 100 square-mile area in central Illinois give results comparable to those of Linsley and Kohler [1951]. For best fit to an expression of the form

$$E = A\,P^{B}\,n^{C} \quad \ldots\ldots\ldots\ldots \quad (1)$$

by minimizing log E the results in Column 1 below were obtained. With storm data grouped into 17 classes on the basis of 20-gage average rainfall the values of Column 2 were obtained. The values of Linsley and Kohler for a 220 square-mile area with grouped data are given for comparison in Column 3.

	1	2	3
A	0.10	0.14	0.186
B	0.57	0.50	0.47
C	-0.62	-0.61	-0.60
Multiple correlation coefficient	0.52	0.88	

An estimate $\bar{x}_n$ of the mean storm rainfall P becomes more meaningful in the equation

$$E = (\bar{x}_n - P) \quad \ldots\ldots\ldots\ldots \quad (2)$$

when some measure is made of the possible error in the estimate. A standard deviation, s, was computed for each of the same class intervals used in determining the values in Column 2. The constants A, B, and C were again determined for (2). The resulting equation is

$$s = 0.17\,P_{0.45}\,n^{-0.57} \quad \ldots\ldots\ldots\ldots \quad (3)$$

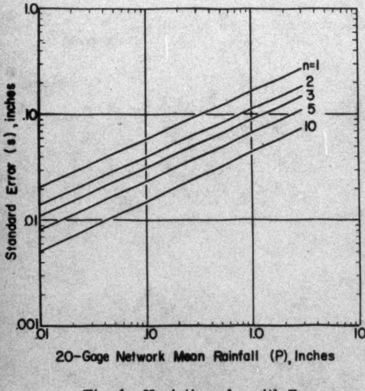

Fig. 1--Variation of s with P for a 100-sq mi area

The multiple correlation was 0.86. Figure 1 shows a graphical relation between P and s for several gage densities.

The 95 pct confidence limits for P were estimated simply by taking 2s and adding and subtracting from the corresponding value of P. The resulting bands are presented for selected values of n in Figure 2. Ninety-four per cent of the sample $\bar{x}_n$ values fell within $P \pm 2s$.

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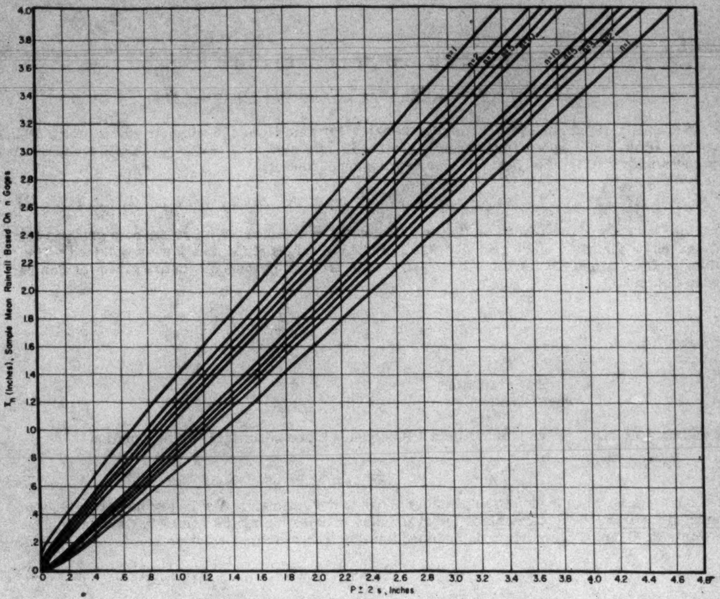

Fig. 2--95 pct confidence bands for 100 square-mile mean rainfall (P)

State Water Survey
Urbana, Illinois

J. C. Neill

Transactions, American Geophysical Union Volume 36, Number 6 December 1955

DISCUSSION OF

"THE EFFECT ON STREAM FLOW OF THE KILLING OF SPRUCE AND PINE BY THE ENGELMANN SPRUCE BEETLE"

by L. D. LOVE

[Trans., v. 36, pp. 113-118, 1955]

Conrad D. Bue (U. S. Geological Survey, Washington 25, D. C., received June 29, 1955)--A rather rough check of the author's analysis was made by the double-mass technique. The double-mass curve of the observed runoff of White River against water content of snow cover in White River basin plotted as a straight line, thereby indicating no change during the period. A similar line for Elk River data broke at about 1946 or 1947, the points for the years 1947 to 1951 falling on a line indicating less runoff in proportion to water content.

The estimates of annual flow of White River in Table 2 were computed back through 1937 by means of the author's regression equation. The double-mass line of estimated White River runoff plotted against White River water content broke at about 1946, and thereafter showed less runoff in proportion to water content. This, of course, was to be expected because one of the variables in the regression equation is the runoff of Elk River, which appeared to have declined in proportion to water content after about 1946.

One conclusion that might be drawn is that the runoff has declined in Elk River since about 1946 for reason unknown, and that in White River some factor - the death of the spruce or some other - has acted to offset a similar decline in runoff. What would otherwise have been a simple comparison is complicated by the fact that Elk River, the control stream, appears to have changed, and instead of one assumption, two assumptions are involved. This would tend to weaken the author's conclusion concerning White River.

The purpose of this discussion is merely to emphasize the difficulty in attempting to associate apparent change in stream flow with change in forest cover. It would be interesting to make an analysis, similar to the author's, of White River on basis of another stream in the area, were a suitable record available.

Milton T. Wilson (U. S. Geological Survey, Salt Lake City, Utah) and Eugene L. Peck (U. S. Weather Bureau, Salt Lake City, Utah, received June 30, 1955)--Love's statement near the close of his paper, "It is possible that some factor (or factors) not associated with the death of the trees is responsible for the change in the stream flow," appears to be more true than the author may have realized.

Conclusions were developed from the results obtained by correlating stream flow of the White River near Meeker, Colorado, with stream flow of the Elk River at Clark and the differences (Elk minus White) in the April 1 water content of the snow on the two watersheds. By using only water content in accumulated snow on April 1 results were inadvertently affected by (1) various time trends, some of which are in the relations between the various parameters used, and (2) significant fall and spring precipitation. Records clearly show that there is a time trend reflecting antecedent conditions in the relation between April 1 water content of the snow and stream flow of the White River and also one in the corresponding relation for the Elk River. It is important to note that the trends in these relations are not always in the same direction. Additional climatological data including fall and spring precipitation are available for developing a much more complete and satisfactory relation between seasonal climatic factors and the water-year runoff.

April 1 water content of the snow alone has a fair correlation with the water-year runoff as shown in Figure 4. The correlation coefficient for this relation is only 0.76. However, if fall and spring precipitation data are used in conjunction with the snow data a relationship may be developed which has a correlation coefficient of 0.87. This relation is shown in Figure 5. The September -

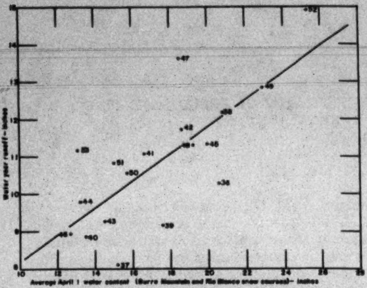

Fig. 4--Relation of April 1 water content of snow to water-year runoff, White River near Meeker, Colorado

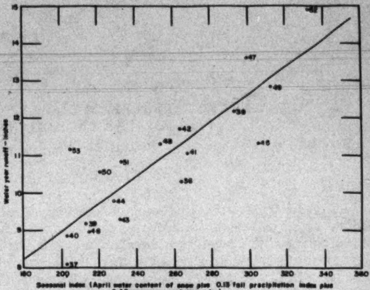

Fig. 5--Seasonal index: water-year runoff relation for White River near Meeker, Colorado

October precipitation totals for the Craig, Hayden, Shoshone, and Rifle climatological stations were used for the fall precipitation index and the April - June precipitation totals for the spring precipitation index. From this relation we may note that there is still some evidence of time trends, however, they are not the same as those developed by the procedure of using only snow survey data. Investigations [McDONALD and LANGBEIN, 1948; PECK, 1954] have shown that these time trends are very often the result of carry-over effects from previous years. If the time trends can be accounted for by indices representing antecedent conditions then the increase stream flow reported by the author would not be due solely to the death of the trees. As an index to the carry-over effects, base stream flow during a winter month may be used. In this case the average stream flow during January was chosen. Figure 6 shows the relation where the January average flow was combined with the seasonal index for a total index to correlate with the water-year runoff. The correlation coefficient for this relation is 0.94. The time trends which were evident in the previous relations are now largely eliminated.

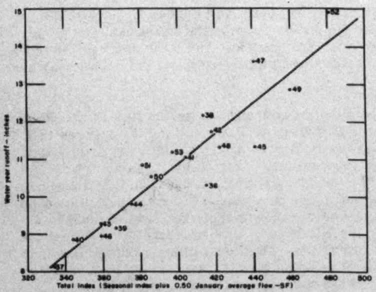

Fig. 6--Total index: water-year runoff relation for White River near Meeker, Colorado

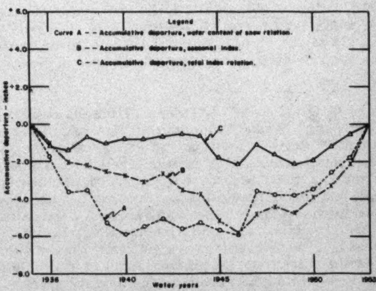

Fig. 7--Accumulative departure from curves of relations of snow water content, seasonal index and total index with water-year runoff, White River near Meeker, Colorado

To illustrate how the time trends were eliminated the curves in Figure 7 were constructed for each relationship. These curves represent the accumulative departures. Curve A shows the accumulative departure for the relationship where only the April 1 water content of the snow was used. In this curve we may see trends similar to those found by the author. The trend for the years 1936 through 1940 is negative but levels off for the years 1941 through 1946. For the later years the trend has been reversed showing that there has been more runoff for the same amount of snow water content than previously. Curve B is for the relation using the seasonal index. Here there is a single downward trend from 1936 through 1946 and then a reverse trend for the later years. Thus, had all of the available data, including the fall and spring precipitation, been used the results would have been modified. Time trends in the fall and spring precipitation account for the differences in the two curves. Curve C shows the accumulative departures from the relationship where the total index was correlated with the water-year runoff. From this curve it is evident that deviations are small and fairly inconsistent. Using the short base of ten years, 1937-1946, Curve C still shows minus departures for the first part of the period and plus departures for the years 1947-1953. The magnitude of the increase is considerably less however than the 2.28 inch increase found by the author and is well within the limits of accuracy of the base data.

Because of the shortness of the base and test periods, certainly only small significance should be attached to any conclusions. It is believed that the results found by the author may be mainly the effects of time trends in climatic factors and not necessarily the result of the killing of the trees by the Engelmann beetle.

It might be assumed by some that the low flow of the winter months as used to eliminate the time trends might have been increased due to the increase in the yield accompanying the death of the trees. As a check a similar study of the records for the Blue River at Dillon, Colorado, was made. Time trends very similar to those for the White River were obtained when only seasonal climatic data were correlated with water-year runoff but the effects were eliminated when the low-flow data were used to develop a total index.

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REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

DOBRIN, MILTON B., Introduction to Geophysical Prospecting, McGraw-Hill Book Co., 1952, 435 pp., $ 7.00.

Dobrin has undertaken "to present, at a fairly elementary level, the fundamental principles and techniques of geophysical prospecting with special emphasis on those phases most likely to benefit the geologist, mining engineer, or executive engaged in exploration for minerals and mineral fuels." This book, written as a text book for a one-semester survey course for students who have had calculus, fills an important void.

The three standard prospecting methods - gravity, seismic, and magnetic - are presented simply but completely, each with discussions of the fundamental physical principles involved and their relationship to the Earth, the instruments and techniques used for measurement, and the interpretation of the data. The newer methods - electrical, radioactivity, and airborne magnetic - are presented in less detail but most of the recent developments are briefly described. Chapters on well-logging methods and on the new techniques of radio position location contain very useful information in these two fields which are a necessary support to geophysical prospecting activities. One of the most useful chapters includes discussions of case histories of oil fields and mining districts, which demonstrate the use and intergration of different geophysical techniques and their interpretation in terms of geologic structure and mineral occurrence. The book is profusely illustrated and all the numerous plates and figures are of high quality.

This book is recommended to all those who wish a complete but brief and elementary survey of the entire field of geophysical prospecting and its application to the search for oil structures and mineral deposits.

J. R. BALSLEY

JAHNS, RICHARD H., (ed.) with 103 contributing authors, Geology of Southern California, California Department of Natural Resources, Division of Mines, San Francisco, California, Bul. 170, Text in ten parts bound separately, x + 620 pp.; Geologic Guides in five parts bound separately, 232 pp., 34 map sheets, numerous illustrations, 1954, $12.00.

The preparation of this reference set was an extensive undertaking. It has been done superbly. Earth scientists interested in any aspect of the geology of Southern California will find here a succinct and exceptionally well-illustrated presentation. It will prove particularly useful for those planning to visit or do field work in Southern California. Teachers will find here valuable information for courses emphasizing either the principles of geology or regional studies.

The contents are as follows: I, General Features; II, Geology of the Natural Provinces; III, Historical Geology; IV, Structural Features; V, Geomorphology; VI, Hydrology; VII, Mineralogy and Petrology; VIII, Mineral Deposits and Mineral Industry; IX, Oil and Gas; X, Engineering Aspects of Geology.

The titles of the Geologic Guides for Selected Field Trips are: (1) Western Mojave Desert and Death Valley Regions; (2) Ventura Basin and Adjacent Areas; (3) Los Angeles Basin; (4) Southwestern Part of the Los Angeles Basin; (5) Northern Part of the Peninsular Range Province.

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NOTES AND PERSONALIA

NOTES

Corrigendum--In the April issue of the Transactions, page 377, are the Constitution and By-Laws of the Geophysical Society of Hawaii (Mid-Pacific Regional Branch, American Geophysical Union). Article 2: Objects should read: The objects of the Society are to serve as the Mid-Pacific Region of the American Geophysical Union and the local branch of the American Meteorological Society and to assist carrying out the objects of these national organizations.

New fellowship program of the National Science Foundation--A plan whereby 40 senior post-doctoral fellowships in science will be awarded has been announced by the National Science Foundation. These will be for persons generally five or more years removed from their science doctorates who have shown increasing proficiency and attainment in their own fields who feel need to explore fields complementary to their specialized training. They must have demonstrated ability and special aptitude for advanced training and productive scholarship in science. Stipends will fall within a $4000 to $10,000 range, adjusted to match, in general, the regular salaries of award recipients, and may be applied toward study or research in an accredited nonprofit institution of higher learning in the United States or abroad. Applications and other information may be secured from the Division of Scientific Personnel and Education, National Science Foundation, Washington 25, D. C., and completed applications must be in by January 16, 1956.

New Earth Science Fellowships established at M. I. T.--A program of fellowships named the Vannevar Bush Fellowships in Earth Sciences has been established at Massachusetts Institute of Technology as a joint educational program of the Institute and the Carnegie Institution of Washington. These are post-doctoral fellowships in the Department of Geology and Geophysics named in honor of Vannevar Bush, who served long as a professor, later as Dean and Vice President at Massachusetts Institute of Technology before becoming President of the Carnegie Institution of Washington. Candidates for the award must have advanced training in mathematics, physics, and chemistry and have a broad knowledge of the Earth Sciences and must have completed all the requirements of a degree of Doctor of Philosophy required by the Institute except the thesis. They will be registered as full-time doctoral candidates at the Institute but devote a part of their residence time at the Geophysical Laboratory in Washington. Fellows will receive a stipend of $200 a month plus tuition for the first 12 months and $225 per month plus tuition for the duration of the fellowship. Interested persons should write to the Chairman, Department of Geology and Geophysics, 24-302, Massachusetts Institute of Technology, Cambridge 39, Massachusetts.

Opportunities in Oceanography and allied fields at Woods Hole Oceanographic Institution--Two predoctoral Associates' Fellowships carrying stipends of $2500 ($3000 for married men) will be awarded for 1956-1957. Applications must be filed by February 1, 1956 with the Director, Woods Hole Oceanographic Institution, Woods Hole, Mass. There are also employment opportunities on the research staff of Woods Hole Oceanographic Institution for those with master's or doctor's degrees in physics, geophysics, biophysics, or mathematical physics and also for those with bachelor's degrees with backgrounds in physics or mathematics. Persons interested in these should likewise get into touch with the Director of the Institution. Summer assistantships are also available.

Government examination for positions open in Geology--The U. S. Civil Service Commission has announced a new examination for geologists in grades GS9 to GS13 ($5440 to $8990). No closing date has been set. Interested persons, should get into touch with the Board of U. S. Civil Service Examiners, Geological Survey, Washington 25, D. C.

Expedition departs for Antarctica to prepare for IGY--The seven ships of Naval Task Force 43 (designated Operation Deepfreeze) left the United States for Antarctica during November, under command of Rear Admiral George Dufek. Rear Admiral R. E. Byrd, in charge of all U. S. Antarctic activities, will join the Task Force in New Zealand. The primary mission of Task Force 43 is to construct the base at Little America, which will serve from January 1957 to January 1959 as the main base of operations for the United States IGY Antarctic Program, which is under the direction of L. M. Gould, President of Carlton College. The Sea Bee battalion accompanying the Task Force will also construct an Air Operating Facility at McMurdo Sound, which will serve as the focal point for all air operations. While the Task Force will leave the Antarctic during March 1956, some of the men will remain behind for the construction of stations at the South Pole and in Marie Byrd Land, with the advent of the summer season in October 1956. During 1956-1957, bases will also be constructed on the edge of the Weddell Sea, and on the Knox Coast.

The U. S. National Committee for the IGY has designated six technical personnel to accompany the expedition this year. Of these, four will return with the Task Force, and two will remain for the the Antarctic winter, one at each station. The latter two will gather preliminary data which will be valuable in setting up the scientific equipment and planning the schedule of observations to be followed during the ensuing two years. In particular, they will make visual observations of the aurora, visual and radar observations of meteors, and will participate in the program of meteorological observations to be carried out by Naval personnel. These two men will also travel with the construction crews who erect the Pole and Byrd Stations, and will take part in the transport of scientific equipment and supplies by air-drop to the Pole Station and by tractor train to the Byrd Station.

Development of the IGY Earth Satellite Program--The Earth Satellite Program, one of the activities planned for the International Geophysical Year by the National Academy of Sciences, is the culmination of an intensive process of study and planning. During the summer and early fall of 1954 several international scientific groups, including the Special Committee for the IGY (CSAGI) of the International Council of Scientific Unions, adopted resolutions urging that the feasibility of launching satellites for scientific purposes be considered in planning for the International Geophysical Year. In view of these recommendations, and in view of the advanced state of U. S. rocketry developments, the Executive Committee of the U. S. National Committee for the IGY appointed a special group to consider the possibility of constructing, launching and observing an instrumented satellite. On the basis of recommendations made by this special study group, the Executive Committee decided that an instrumented satellite was of great potential scientific importance, that it was technically feasible, and that it was a logical extension of the USNC-IGY program of rocket research in the upper atmosphere. A resolution to this effect was transmitted to the President of the National Academy of Sciences and the Director of the National Science Foundation on March 14, 1955. Preliminary studies of the nature of the satellite and the launching mechanism were continued, and in May 1955 the U. S. National Committee transmitted a proposal for the construction and launching of several satellites to the National Science Foundation. On review of this proposal, and on the personal approval of President Eisenhower, the historic announcement of July 29, 1955 made known this Government's willingness to undertake the project. At the same time, the Chairman of the U. S. National Committee informed the Chairman of CSAGI of this decision, and invited the participation of other nations in the observation and scientific application of the satellites.

It is planned to build approximately twelve instrumented birds, with the expectation that at least five will be successfully launched into their orbits, circulating about the Earth for periods of two weeks to several months at heights between 200 and 800 miles. The following types of observations are under consideration: (a) determination of outer atmosphere densities by observation of the air-drag effect on the satellite's orbit; (b) obtaining of more accurate measurements of the Earth's equatorial radius and oblateness and of intercontinental distances and other geodetic data than are presently available; (c) long-term observations of solar ultraviolet radiation; (d) studies of intensities and fluctuations in intensity of the cosmic and other particle radiations impinging on the atmosphere; (e) determination of the density of hydrogen atoms and ions in interplanetary space; (f) observations of the Störmer current ring; (g) if possible, determination of the distribution of mass in the Earth's crust along the orbital track. More information concerning the program may be found in the November 25, 1955, issue of Science, pages 1003-1005.

Coordination of the Satellite Program--On behalf of the National Academy of Sciences and the U. S. National Committee for the IGY, Joseph Kaplan has announced the membership of the USNC-IGY Technical Panel on the Earth Satellite Program as follows: R. W. Porter, Chairman (General Electric Company); Hugh Odishaw, Secretary (National Academy of Sciences); H. E. Newell, Jr. (Naval Research Laboratory); W. H. Pickering, (California Institute of Technology); A. F. Spilhaus, (University of Minnesota); Lyman Spitzer, Jr. (Princeton University); J. A. Van Allen, (State University of Iowa); F. L. Whipple, (Smithsonian Astrophysical Observatory and Harvard University). The functions of this panel are analogous to those of the other twelve technical panels of the U. S. National Committee in the various IGY disciplines. The Technical Panel on the Earth Satellite Program has fundamental responsibilities, acting on behalf of the USNC, in developing, coordinating, and directing the scientific satellite efforts. The Panel, with such additional membership and consultants as are necessary, expects to utilize contributions from many scientists and institutions, a feature that has characterized the planning of all IGY programs under the auspices of the USNC.

Fiftieth Anniversary of the Illinois Geological Survey--On November 11, 1955, the Fiftieth Anniversary of the Illinois Geological Survey was celebrated in Urbana, Illinois. A large group of scientists and others from coast to coast gathered to take part in the festivities, and warm tribute was paid to M. M. Leighton who served as Chief of the Survey from 1923 to 1954. George W. White, Professor of Geology at the University of Illinois, served as representative of the AGU, but General Secretary Sayre and many other members of AGU were also in attendance.

Recent Scripps Expedition to Central and South American Pacific Waters--The research vessels Spencer F. Baird and Horizon of the Scripps Institution of Oceanography have recently returned from an oceanographic expedition in the Pacific Ocean off Central and South America.

Geophysical Institute proposed for Hawaii--Studies have been under way for some time for the establishment of a Geophysical Institute at the University of Hawaii, this being a center for the vast areas of the Pacific on which geophysical information is now quite meager. A bill has been introduced into Congress (HR7754) to authorize the establishment of the Institute and a million dollars for its construction and establishment.

Meeting of the Eastern Snow Conference--The 13th Annual Meeting of the Eastern Snow Conference will be held at Dartmouth College, Hanover, New Hampshire, February 9, 10, 1956. Those interested in taking part in this meeting should get into touch with the Secretary, Dean B. Bogart, 526 Federal Building, P. O. Box 948, Albany 1, New York.

New Physical Sciences Building at the University of California at Los Angeles--A new building to house the Departments of Meteorology, Mathematics, and Astronomy is being built on the north side of the Court of Sciences on the Los Angeles Campus of the University of California. It is an L-shaped structure containing over 100 rooms including class, laboratory, office and conference rooms, with a lecture hall seating about 125. The building is scheduled for completion in January 1957 and will cost about $1,700,000.

Soviet Professional Manpower--In a recent release, the National Science Foundation has noted that the Soviet Union is graduating almost twice the number of technical specialists in certain fields as the United States. Between 1928 and 1954, the Soviet Union graduated 628,000 engineers as against 480,000 in the United States. Our agricultural graduates totaled 133,000, compared with 244,000 in the Soviet Union. In medicine the Soviet Union graduated 320,000, as compared with 148,000 in the United States. Further details of this study are presented in Soviet Professional Manpower by Nicholas DeWitt, being published by the National Science Foundation in cooperation with the National Academy of Sciences - National Research Council. It is pointed out that in training these personnel, the Soviet Union is sacrificing other elements that democracies regard as important. For example, the Soviet Union has a small number of graduates in the humanities, whereas between 65 and 70 pct of all graduates in the United States major in the social sciences or liberal arts. The book is for sale by the Superintendent of Documents at $1.25 a copy.

New series in oceanography--Volume One of Andhra University Memoirs in Oceanography (Andhra University Series no. 49) has been received in the United States. It contains 15 papers on topics relating chiefly to local oceanographic problems.

New Glossary of Hydrology--Nine Asian hydrologists associated with various international agencies have recently completed a Glossary of Hydrology of some 130 pages and about 1000 terms used in the hydrologic field. The original draft of the glossary was prepared by the Bureau of Flood Control of the U. N. Economic Commission for Asia and the Far East (ECAFE), with its final version worked out jointly by the ECAFE and the World Meteorological Organization. The glossary will be published early in 1956 and will be in English.

PERSONALIA

Lloyd V. Berkner, President of Associated Universities Incorporated in New York, has been given an honorary degree of Doctor of Science by the Brooklyn Polytechnic Institute.

Joseph C. Boyce, Associate Director of Argonne National Laboratory, has been named Dean of the Graduate School of Illinois Institute of Technology.

John S. Burlew has been named as the Director of Franklin Institute in Philadelphia.

Marion R. Carstens, Associate Professor of Civil Engineering at Georgia Institute of Technology, has been named the recipient of the J. C. Stevens Award of the American Society of Civil Engineers for his discussion of the paper, Mechanics of Manifold Flow.

Samuel Coroniti has resigned his position as Head of the Section on Atmospheric Electricity of the Air Force Cambridge Research Center and has taken up duties as a physicist with the Raytheon Manufacturing Company of Waltham, Massachusetts.

Albert P. Crary, research scientist of the Geophysics Research Directorate, Air Force Cambridge Research Center, will be the Deputy Chief Scientist of the IGY Antarctic program with responsibility for studies in glaciology, seismology, and gravity in Antarctica.

Gabor Dessau, who retired in September, 1953, from service with the Italian Government and has been serving as Charge de Cours of mineral deposits at the University of Naples and in charge of Centro Ricerche Minerali Radioattivi of the ENI-AGIP group, has been appointed by UNESCO to advise on the setting up of a Geological Engineering and Mining Department at the Hebrew Institute of Technology at Haifa, Israel.

Oliver H. Gish, retired physicist of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, serving as part-time consulting physicist with the U. S. Air Force and the U. S. Navy, has been appointed Visiting Professor of Physics at Southern Illinois University for the current academic year.

Richard C. Hubley, of the Unviersity of Washington, has been appointed Coordinator of the glaciology program of the U. S. National Committee for the International Geophysical Year.

Edward O. Hulburt, who will retire from his position as Director of Research of the Naval Research Laboratory at the end of 1955, has accepted the appointment as Senior Scientist of the National Academy of Sciences' Committee for the International Geophysical Year.

Earl Ingerson, Chief of the Geochemistry and Petrology Branch of the U. S. Geological Survey was named the recipient of the Arthur L. Day Medal awarded by the Geological Society of America at their 68th Annual Meeting held in New Orleans, November 7-9, 1955. This is awarded for scholarly accomplishments in the fields of chemistry and physics as related to geology.

E. C. La Fond of the U. S. Navy Electronics Laboratory left September 1, 1955 to spend another academic year as Professor of Oceanography at Andhra University, Waltair, India.

Chester R. Longwell, Professor of Geology at Yale University, is now on terminal leave and will retire June 30, 1956. He has moved to Menlo Park, California, and is continuing his research work at the facilities of the U. S. Geological Survey with respect to problems of southern Nevada.

John S. McNown, Professor of Engineering Mechanics, University of Michigan, has been named the recipient of the J. James R. Croes Medal by the American Society of Civil Engineers for his paper entitled Mechanics of Manifold Flow.

R. C. Peavey, formerly with the Central Radio Propagation Laboratory of the National Bureau of Standards, has been named Administrative Officer of the U. S. National Committee for the International Geophysical Year.

Paul A. Siple, Director of Scientific Projects and Environmental Living for the Commander of Task Force 43, has left for New Zealand to join the Task Force en route Antarctica where the expedition will set up bases for the IGY program of the United States.

Harry Wexler, Director of Meteorological Research of the U. S. Weather Bureau, has been appointed Chief Scientist of the Antarctic program of the U. S. National Committee for the International Geophysical Year.

William E. Wrather, Director of the U. S. Geological Survey, has been given the Distinguished Service Award of the Department of the Interior for his long and outstanding work in the Department. He originally joined the Geological Survey in 1907, subsequently leaving to engage in commercial geological work, and then returning in May, 1943, as its Director.

Th. Reinhold, Director of the Geological Survey of the Netherlands, died in August, 1955, at the age of 64, after a long illness.

Ernst Wanner, Vice Director of the Swiss Meteorological Bureau, President of the Swiss National Committee of IUGG, and Vice President of the International Association of Seismology and Physics of the Earth's Interior, died November 4, 1955, at the age of 55.

MINUTES OF EXECUTIVE COMMITTEE MEETING, AMERICAN GEOPHYSICAL UNION OCTOBER 15, 1955

The meeting was called to order at 13h 46m in the Board Room of the National Academy of Sciences - National Research Council Building, 2101 Constitution Avenue, Washington, D. C., by President James B. Macelwane.

Present--L. R. Alldredge, W. W. Atwood, Jr., K. Hilding Beij, Hugo Benioff, L. V. Berkner, R. R. Bodle, Walter H. Bucher, James J. Capello, S. D. Cornell, Ross Gunn, Ross R. Heinrich, H. H. Hess, Albert J Hoskinson, W. C. Jacobs, J. W. Joyce, Joseph Kaplan, Walter D. Lambert, H. E. Landsberg, James B. Macelwane, J. Namias, James A. Peoples, Jr., R. J. Russell, A. N. Sayre, Waldo E. Smith, E. H. Vestine, and H. G. Wilm. The following were excused because of absence from the city or for other reasons: Francis Birch, Harry F. Blaney, Perry Byerly, H. R. Byers, P. E. Church, E. A. Eckhardt, Maurice Ewing, John A. Fleming, H. R. Joesting, W. B. Langbein, E. S. Larsen, Jr., Ray K. Linsley, Gordon A. Macdonald, L. A. Maynard, W. H. Munk, A. C. Redfield, Frederick D. Rossini, M. O. Schmidt, L. B. Slichter, H. T. Stetson, F. J. Veihmeyer, J. T. Wilson, and George P. Woollard.

Approval of minutes--The minutes of the Executive Committee meetings on May 1 and 4, 1955, published in the August, 1955, issue of the Transactions (pp. 739-750), were approved.

General Secretary's Report

The last report of the General Secretary was that of May 1, 1955, presented in summary form at the meeting of that date and published in the August, 1955, issue of the Transactions, pages 739-742. On June 6 our General Secretary, John Putnam Marble died. Subsequently the Executive Committee requested that I undertake to complete his unexpired term. I entered upon my duties in this capacity on June 27. This report covers the period during which I have been General Secretary, and also the period from our last meeting.

Publications--The following issues of the Transactions have been printed and distributed since our last meeting:

June, 1955	192 numbered pages, edition of 6200
August, 1955	182 numbered pages, ten unnumbered pages including six pages of paid advertising, edition of 6100

The October issue, containing 184 numbered pages and eight unnumbered pages, is now at the printers and should be delivered to us later this month. The edition ordered is 6100.

The Editorial and Publication Committee has been very busy since our last meeting, not only in its regular work but also in its efforts to decrease our backlog of papers, in making arrangements for the solicitation of advertising, and in working out arrangements and details for the publication of the Transactions in new format.

The Subcommittee on Advertising (John Lyman, Chairman; George T. Faust; and Walter T. Wilson) recommended acceptance of the proposition of William A. James of New Haven, Conn., to serve as our advertising representative. For some years he and Mrs. James had been advertising representatives for the American Scientist, the American Scholar, and the Yale Review. Late in May, arrangements were worked out, and he undertook the task with vigor and tact. However, on August 3, 1955, he died. He had obtained six pages of advertising at a base price of $ 100 per page for our August issue, and had obtained contracts for additional advertising in subsequent issues totalling about $ 1200. Mrs. James, who began this activity years earlier, and subsequently interested Mr. James in it, had gradually withdrawn from it prior to his death. However, she now desires to assume his work. Therefore, we have worked out an arrangement whereby she will continue to fill out the year for which arrangements were made with Mr. James with the hope and expectation that the arrangement might continue rather indefinitely into the future. Mr. James had expected to secure at least 12 pages of advertising for the October issue. However, because of his death and the fact that our August *Transactions* came out late due to a strike at the plant of our printer and thus could not be used effectively in selling additional advertising, our total number of pages of advertising in the October issue is seven. We believe that Mrs. James will pursue this matter vigorously. She points out that December is a bad month to obtain new advertising contracts. However she expects to have a number of additional pages in the first issue of 1956. Our gross return from advertising to date, including that in the October issue, will be about $ 1100 and our total expense about $ 1000. We are hopeful that this margin will widen greatly.

The Subcommittee on Format (Walter B. Langbein, Chairman; Charles S. Gilman; and David G. Knapp), has been working on plans for the change-over. Mr. Langbein will give his report of the work and findings of this Subcommittee which is now working out final arrangements with the Waverly Press for the publication of our *Transactions* beginning with the February, 1956, issue.

We have continued to whittle down on our backlog of papers with the aid of the $ 4000 grant of the National Science Foundation, and it appears that we are approaching the optimum backlog.

Our Committee on Cloud Physics of the Section of Meteorology arranged a Conference on the Physics of Cloud and Precipitation Particles at the Woods Hole Oceanographic Institution on September 7 to 10, 1955, utilizing the balance of the funds available on the Air Force contract for the Portsmouth Conference. The Conference was an outstanding success, and the papers presented were of uniform excellent quality and served to bring this active field up to date. Our contract at present calls for supplying a fully edited manuscript only, but there is the thought that the contract be amended, giving AGU full publication rights and rights to sale, and that this then be Monograph No. 1 of the new monograph series which the Executive Committee approved at our meeting on May 1. It is believed that the sale of the publication at a reasonable rate will defray the cost of setting up the master copy and the cost of printing. The Editorial and Publication Committee recently considered this, approved, and so recommends to the Executive Committee, though at that time, it was thought that the Air Force and the ONR which supplied the funds under this contract, might add funds to defray the full cost of setting up the master copy. This has been refused. It is proposed that a revolving fund of about $ 1500 be established to take care of expenses before returns from sales come in. Later a formal recommendation will be made.

Membership--Data are:

Membership, April 27, 1955	5070	
New members, April 28, 1955 to Oct. 10, 1955, including 9 applications in process	93	5163
Resigned	44	
Inactive	2	
Dropped (tentative)	136	
Deceased (reported since April 28)	7	189
Membership as of October 10, 1955		4974

That is the first time our membership has decreased, and as pointed out by the General Secretary in May this is not really satisfactory, but until we have our *Transactions* in the new format we probably can not expect to increase our membership. However, there is ample evidence that we have not reached the saturation point. It is felt that the International Geophysical Year and the American activity in it should give substantial impetus to increased membership. There are a good many persons working actively on one phase or another of this program who are not now members. We are hopeful that at an early date these people might be approached.

The following seven deaths have been reported to the Union office since our last meeting: Carl F. Giffey, March 14, 1954; Harry M. Ryder, July 6, 1954; Lafayette B. Herring, March 3, 1955; George Hartnell, May 20, 1955; John Putnam Marble, June 6, 1955; Albert E. Cummings, July 20, 1955; Robert B. Campbell, August 16, 1955.

Dues unpaid--	Owe for 1/2 of 1955	10	351
	Owe for 1955	341	
	Owe for 1/2 of 1954 and 1955	5	234
	Owe for 1954 and 1955	229	
	Owe for 1/2 of 1953, for 1954 and 1955	14	136
	Owe for 1953, 1954, 1955	122	

In accordance with the action of the Executive Committee, further effort has been made to get those of the last group back into active membership, and the number has been reduced from 157 in May to 136 as of October 10. There may be further response, but the 136 have been tentatively entered on the above tabulation as dropped.

There are two particular situations that should have the special attention and decision of this Committee for which we believe there is perhaps no precedent. The first of these relates to a member of this Executive Committee, who is President of one of the Sections but who has not paid dues since 1952 and who should be dropped under the rules of the Union (and is now so listed). He is, however, also an officer of an International Association and so is ex officio a member of this Committee. The usual letters have been sent to him the same as any other member delinquent in dues, and the Executive Secretary has sent him a personal note, all of which have brought forth no response. This matter will be referred to the Executive Committee for action.

Another of these persons tentatively listed as dropped has been very active in the Union in the past, having served as President of one of the Sections and advanced the Union's interests very greatly in at least one other capacity. He has received the usual communications and has written wondering what can be done to remit his dues. The guidance of the Executive Committee will be sought in this situation also.

Finances--The office has prepared a financial statement for the year ending June 30, 1955, which will subsequently be presented by the Committee on Audit for action. The report indicates that our net increase in cash balance was about $1000 not counting additions to our Permanent Fund.

The statement below is as of October 1.

	Oct. 1, 1955	Oct. 1, 1954	Oct. 1, 1953
Cash balance	$ 14,152	$ 11,208	$ 11,860
Permanent Fund	12,180[a]	10,657[a]	9,171[a]
Emergency Fund	1,000	1,061	1,028
T. M. and E. Award Fund	985	211	0
	$ 28,317	$ 23,137	$ 22,059

[a]Does not include interest on $ 2,368 of U. S. Savings Bonds.

Detailed figures for the past year are available for inspection.

A number of years ago the Executive Committee set up an Emergency Fund of $ 1000. This Fund has remained intact and by June 30 of this year had drawn interest accumulating to nearly $ 100. Noting that the Fund was set up as $1000, the General Secretary accepted the recommendation of the Executive Secretary that the amount be kept at $1000 except as there may be withdrawals, with the earnings being transferred to the Permanent Fund.

At the time of his death, Robert E. Horton left a fund of $ 5000 for the completion and publication of unfinished manuscript. Several manuscripts were completed and charged to this fund, but there is residual of about $1000 in the general cash balance that pertains to this fund. There is no prospect of publishing further papers, and it is believed that AGU has fulfilled its obligation both morally and legally and that therefore balance be transferred to our general reserve, or some other appropriate disposition of it should be made.

Office staff and jobs--The office staff consists of James J. Capello, Assistant to the Executive Secretary and Assistant Editor; Milena Vaneckova, Clerk-Typist; and Zdenka Dalecka, Electromatic Operator and Assistant to Editor. Elsa M. Sarmiento, Clerk-Typist, who came with us at the beginning of the year, left May 5, 1955, to return to her home in Peru, and was not replaced except by a temporary summer worker; Glenda Quinn, who has served as Clerk-Stenographer since June 1954, devoting much of her time to the preparation of the report under the Air Force contract, has returned to college but is still devoting a small amount of time to work of the office. We are looking for a replacement and in the interim have engaged for the month of October the services of Llewellyn W. Clague, who worked with us as an office boy in years past and who must return on November 1 to his studies at Antioch College. As a part-time office boy, we have the services of Stephen Dice. Activities continue under the direct supervision of Waldo E. Smith, Executive Secretary.

Status of Air Force contract--As noted above, there was a balance left in the contract funds provided by the Air Force. This has been used to good purpose for a second conference, at Woods Hole. Many of the papers presented at the primary conference held in Portsmouth in May, 1954 were delayed by clearance, but the master copy of the report on the conference, including all the papers and the essence of the verbatim discussion, was completed and delivered to the Air Force at the end of August, this completing what is now considered Phase 1 of the contract. Phase 2 relates to the Woods Hole Conference on which a report was given earlier.

Status of Bibliography of Hydrology, 1951-1954--The compilation work under this contract, undertaken by Ray K. Linsley of Stanford University, is now complete and he is in the process of preparing the index. The editing of the manuscript by the Executive Secretary is about half complete, and Mrs. Nancy Ing, who formerly served as Electromatic Operator and Assistant to the Editor, is setting up the master copy in her home. The master copy should be ready for delivery to the Bureau of Reclamation by November 30, 1955.

International matters--Unofficial word has been received that the next General Assembly of the IUGG scheduled for Buenos Aires in early September, 1957, will not be held there and that the Council of IUGG will meet early in March, 1956, to select a new site. We are hoping for confirmation or refutation of this information before the time of the meeting.

Matters relating to the Union and its affairs--A Regional Meeting of AGU was held in Iowa City, June 16-17, 1955, and Regional Chairman M. C. Boyer reports that this was a very good meeting and that tentative plans have been made to meet in the St. Louis area in 1956.

We have the following representatives on NRC groups:

Division of Earth Sciences: Harry H. Hess
Division of Physical Sciences: Walter H. Bucher
American Geological Institute, Board of Directors: E. A. Eckhardt and H. R. Joesting
U. S. National Committee on International Geophysical Year: A. N. Sayre, in his capacity as General Secretary

Various committees, of course, include many members of AGU serving because of their special qualifications.

The resolutions passed at the Annual Meeting last spring have been forwarded appropriately. Quite a number of responses have come in.

The following NAS-NRC officials are *ex officio* members of our Executive Committee:

President, National Academy of Sciences: Detlev W. Bronk
Chairman, National Research Council, none currently designated; S. D. Cornell invited to attend.
Chairman, Division of Earth Sciences: Richard J. Russell
Chairman, Division of Physical Sciences: Brian O'Brien
Chairman, Division of Chemistry and Chemical Technology: Frederick D. Rossini
Chairman, Division of Biology and Agriculture: L. A. Maynard
Director, Office of International Relations: Wallace W. Atwood, Jr.

Our representatives on the Council of the AAAS are in process of being designated. (Werner A. Baum and A. Nelson Sayre have subsequently been named.)

Special delegates--Daniel Linehan served as our representative at the inauguration of Albert B. Bronwell as President of Worcester Polytechnic Institute on April 30, 1955. The Executive Secretary attended a meeting of the Council of Engineering Societies' Secretaries in Philadelphia on May 24-25, 1955. Elliott B. Roberts served as our representative to the Sixth General Assembly of the Pan American Institute of Geography and History in Mexico City, July 25 to August 6, 1955. George W. White of the University of Illinois served as our representative at the 50th anniversary of the establishment of the Illinois State Geological Survey on October 11, 1955; our General Secretary and other members of AGU were also present at this gathering. Lloyd V. Berkner and J. L. Rich have been designated as our representatives at the Fifth National Conference of UNESCO to be held in Cincinnati, Ohio, November 3-5, 1955. Joel B. Cox has been requested to serve as our official delegate to the inauguration of Paul S. Bachman on November 9, 1955, as the fifth President of the University of Hawaii.

Meetings--As will be noted by the Chairman of the Committee on Meetings, four Regional Meetings are in prospect for the fall and winter. Our Annual Meeting will be held as previously announced on April 30 - May 2, 1956.

Quarters--Our present arrangement for quarters in the Administration Building of the Carnegie Institution of Washington continue through January, 1956. It is hoped that we may continue to occupy our present quarters, and late this year negotiations will be entered into.

Committees--Two changes have taken place in our Executive Committee since our last meeting. Frederick D. Rossini has succeeded William J. Sparks as Chairman of the Division of Chemistry and Chemical Technology of NRC and thus becomes a member of our Executive Committee, and L. A. Maynard has succeeded Paul A. Weiss as Chairman of the Division of Biology and Agriculture of NRC and likewise becomes an *ex officio* member of this Committee. We welcome these new members.

Items of interest--There has been considerable discussion in the last several months about the establishment of an Institute of Geophysics in the University of Hawaii, and in the spring Kirk Stephenson of the National Science Foundation took leave from his work to make a survey of possibilities for the University of Hawaii and reported back favorably. The Executive Secretary has been invited to take part in the discussions relating to this and in June joined a group to talk this matter over with Mrs. Joseph R. Farrington, Delegate from Hawaii. A Bill has now been introduced before Congress (HR 7754, 84th Congress, first session) for the establishment of this Institute and authorizing a million dollars for buildings and equipment.

During the past several months there has been considerable discussion about the founding of a Society of Geochemists which would be affiliated with the Geological Society of America. We understand that plans for this are proceeding and that formal steps to this end will presumably be taken in New Orleans in November in connection with the meeting of the Geological Society of America.

In the late spring we reviewed the publication to be put out by B'nai B'rith entitled Careers in Geophysics and offered suggestions that we felt would be helpful in strengthening this document. We believe that these recommendations were largely followed.

During the summer months we undertook a similar review for the Bureau of Labor Statistics, going over the draft of their pamphlet entitled Educational Requirements for Employment of Geophysicists.

Respectfully submitted,

A. N. Sayre
General Secretary

Action on the General Secretary's report--The report was accepted.

Recommendations of the General Secretary--The General Secretary recommended that we should review our relationship with the American Geological Institute, noting that AGU is a union of individual geophysicists engaged in the scientific work of geophysics while AGI is an association of institutions, associations, and societies that are concerned essentially with geological work. He also recommended that the Executive Secretary be given authority to sign checks on the Union's accounts, noting that at the present time the General Secretary is a prime signator and that in his absence the President and the Vice President may sign. It frequently occurs that all three are out of town and the securing of signatures on routine salary payments and so on involves some special effort. After considerable discussion it was agreed that arrangements be made for such provision in By-Laws 18 or 19, or both and that the Committee on Statutes and By-Laws be authorized to prepare the particular wording in order that this may be implemented (see Appendix 3).

President's remarks--The President expressed the thought that upon the publication of our *Transactions* in the new format we should make an intensified effort to secure new members and that he does not feel that we have reached the saturation point with respect to membership. He suggested that we should survey the membership lists of other organizations and that the active workers in various agencies of the International Geophysical Year should offer many good prospects for membership. He noted that subsequently a report of the Committee on International Participation would be forthcoming and that he felt by the time of our meeting in May, 1956, we would have some concrete proposals to make to the International Union of Geodesy and Geophysics.

Reports of Standing Committees

International Participation--Chairman Berkner noted that the Committee had held a meeting during the Annual Meeting in May, 1955, and another on the morning preceding this Executive Committee meeting. The Committee has been looking at the very broad problem of the relationship of AGU and IUGG to science and to the improving of the organization of IUGG as a more effective international instrument in science. Three subcommittees (one on Organization of Delegations, the second on Handbook of Statutes and By-Laws of IUGG and its Associations and the History and Background of IUGG, and the third on the Financial Structure of IUGG) have been established, and reports from each of these subcommittees will be completed in early December and integrated into a single report of recommendations for action by the Executive Committee at its meeting in May, 1956. He noted that a survey of the membership of those listed as the leading geophysicists in the various branches of geophysics had resulted in a finding that about 75 per cent are members of AGU and that this information was being passed on to the Committee on Membership in order that it may expend some effort on the other 25 per cent.

It was also reported that Argentina had withdrawn its invitation to hold the General Assembly there in 1957 and that the Committee on International Participation had voted unanimously that the meeting be held elsewhere in 1957 and that it not be postponed. The Executive Committee endorsed this proposition and thus gave the Chairman the authority to pursue this matter with the full backing of the Executive Committee.

President Macelwane noted that L. V. Berkner was elected President of the International Council of Scientific Unions at the meeting in Oslo, Norway, in August, 1956, and in response Berkner noted that while this is a great honor to him it also involves the assumption of substantial responsibility, especially because ICSU is undertaking reorganization to make it a much more effective organization. He noted that its dues structure has been markedly changed in such a way that it would furnish a good precedent to IUGG. The new dues structure should produce enough revenue to carry on the functions effectively and not depend upon subventions from UNESCO for its regular work.

He noted that an important part of the discussions in Oslo related to the International Geophysical Year. While this involves international coordination of research, at the same time it leaves the individual nations free to do their own particular phase of the research job in their own way and it thus serves as a stimulus to national pride and opportunity.

Editorial and Publication--Chairman Sayre noted progress in plans for the new format and presented the report of the Subcommittee on Format (Appendix 1). The report was accepted and the plans outlined were approved. It was noted that the Committee on Cloud Physics of the Section of Meteorology (Helmut Weickmann, Chairman) had arranged a Conference on the Physics of Cloud and Precipitation Particles under the auspices of the Air Force Cambridge Research Center, Office of Naval Research, and AGU, utilizing the balance of funds under contract with the Air Force. The Conference was held in Woods Hole, September 7-10, 1955, and was considered an outstanding success with papers of uniformly high quality. The recommendation was made by the Editorial and Publication Committee that this be set up as the first of the monograph series established in principle last May by the Executive Committee and that this be published in the format of the present Transactions provided arrangements could be worked out with the contracting agency to give the AGU full rights to the distribution and sale of this beyond a limited small number provided to the agency without charge. The Executive Committee felt that this might be put in the new format in which the Transactions of 1956 will appear even though this would cost somewhat more, and a motion was made and passed that a revolving fund of $ 2500 be established in order to proceed with Geophysical Monograph No. 1.

It was noted that a number of years ago the Executive Committee set up a revolving fund of $ 1500 for the preparation of the 25-year index (1920-1944, inclusive) and that the recommendation had been made that we prepare a ten-year index (or rather 10 1/2 years from August, 1945, through December, 1955, covering 11 volumes of the bimonthly Transactions). It was noted that the revolving fund previously set up was still intact and that the index previously published had more than paid for itself. It was voted that we should proceed with plans for the ten-year index.

Nominations--Chairman Landsberg submitted a slate of nominees for the officers of the Union. Two nominees were offered for President and General Secretary, but the slate included only one for Vice President. The Committee was requested to proceed with the securing of a second nominee for Vice President which should be added to the list of official nominees. (The final list of nominees is published on pages 1119-1120 under Special Announcements in this issue of the Transactions along with the list of official nominees for the Sections.)

Statutes and By-Laws--Chairman Bodle noted that there were minor errors in the Statutes and By-Laws of the Geophysical Society of Hawaii as adopted last December and published on pages 377-378 of the April, 1955, issue of the Transactions, this relating to the relationship of the Society to the American Meteorological Society. It was felt that this could be handled as a corrigendum in a subsequent issue of the Transactions.

There was discussion concerning revision of Article 3(a) of the Statutes, and it was finally agreed that steps should be taken to modify this Article to read:

Article 3(a)--Members in good standing for a total of 25 years (or 15 years for members joining before January 1, 1946), following retirement from active professional service because of age or disability and upon written notice to the General Secretary, shall be extended the complete privileges of membership without further payment of dues. The Executive Committee may also extend these privileges to members for extraordinary services to the Union.

This will require approval of the National Research Council and will be placed on the ballot to be sent to members in the winter in convention with the election of offices.

Budget--Chairman Beij reported that the financial condition of the Union is satisfactory and recommended that an adjustment be made in the salary of the Executive Secretary immediately to bring this into line with the salaries of similar positions. This was approved.

Meetings--In the absence of Chairman Adkins, the Executive Secretary read a brief statement noting four regional meetings as follows: the Mid-Pacific Regional Meeting in Honolulu, November 15-17, 1955, with a field trip following arranged by the Geophysical Society of Hawaii serving as our Regional Committee and the local branch of the American Meteorological Society; the Pacific Northwest Regional Meeting in Portland, Oregon, November 17-18, 1955; the meeting in Atlanta, Georgia, December 27-29, 1955, in cooperation with the American Association for the Advancement of Science (a joint session will be held on the afternoon of December 28, with the American Meteorological Society, and on the mornings of December 27, 28, and 29 a Symposium on the Geophysical Year will be held, cosponsored by AGU with the AAAS, the U. S. National Committee for IGY, and the National Science Foundation); the Pacific Southwest Regional Meeting to be held at the University of California in Los Angeles, January 26-27, 1956; and our Thirty-Seventh Annual Meeting to be held in Washington, April 30 - May 2, 1956, with a Symposium on the Antarctic, April 26-27, 1956, of which AGU is cosponsor with the U. S. National Committee on the International Geophysical Year and the National Science Foundation. The program is being arranged by L. M. Gould, Chairman of the Panel on the Antarctic for the U. S. National Committee for IGY.

Membership--Chairman Hiatt was absent. While it was noted that the every-member-get-a member effort of a year ago was not the success for which we had hoped, it brought in perhaps 150 new members over what would have been secured without the effort. During the past months it has seemed that, with a change in format and a small dues increase in immediate prospect, an effort to secure new members might be more fruitful early in 1956 than during the closing months of 1955. The thought was expressed that the new format might well bring in a thousand new members in a few months if effort is made to get into touch with them.

Audit--Chairman Sayre reported that an audit of the accounts of the Union to June 30, 1955 showed the books to be in good condition, and presented the statement for the year's operations as set forth in Appendix 2. The report was approved.

Award in Terrestrial Magnetism and Electricity--Chairman Gunn noted that he had had no great success in raising funds for this Award and that the total in hand is now about $ 1000. It was noted that about $ 2000 had been received earlier and had been turned back to be considered as pledges until our goal is more nearly reached, that another $ 1000 had been pledged which would bring the total fund up to about $ 4000, and that if we made the goal $ 5000 with the idea of making this an award rather than a medal, it would be a fund sufficiently large ot make the award worth while. No action was taken at this time.

Resolutions--Chairman Vestine read a draft resolution to the effect that the Honorary President be given a small annual honorarium. This was discussed at length, and it was generally agreed that the Executive Committee could not legally do this. A number of members present indicated willingness to contribute annually to a fund outside of AGU from which this honorarium could be paid. No final action was taken pending further developments.

Corporation membership--A letter was read from Chairman Eckhardt, who was unable to attend this meeting, in which he indicated that it had been quite impossible for him to do anything about this assignment and that he thought AGU should find someone else to look after this problem. Berkner noted that in connection with raising funds for URSI 12 regions were set up, each under a chairman, and each with a committee to secure these funds, and that efforts were quite successful. He felt that it is important to set a time limit, that such an effort might similarly be effective in largely increasing the number of our Corporation Members, and that the effort of setting up the regional committees might well be done through the office of AGU. The General Secretary and the Executive Secretary were given the responsibility for working out the plan.

Reports of Sections

Hydrology--H. G. Wilm noted that the International Association of Hydrology is making plans for a Symposium on Hydrology to be held in southern France in the summer of 1956 and that plans for the program are now in progress. This is to be in honor of the centennial of Darcy's monumental work.

He noted further that the Section of Hydrology has intermittently in the past made paper awards for the Best Paper and the Best First Paper, and that steps are now under way to revive the plans for the award to the Best Paper. The General Secretary noted that there is a balance of about $ 1000 in the fund left by Robert E. Horton and suggested that this might be used to finance this effort. It was voted that the balance be absorbed in the general funds of the Union and that an annual appropriation be made from Union funds on the order of $ 50 in order to defray the costs of engrossing and other work involved in the certificate of award for the Best Paper in Hydrology.

Affiliated Organizations

American Geological Institute--There was some further discussion of the aims and purposes of the American Geological Institute, noting especially that AGU, in approving the new Statutes and By-Laws of AGI on May 2, 1954 (Transactions, August, 1954, p. 685), had made certain comments and recommendations concerning the name and scope of AGI. A special committee was appointed by AGI for this purpose which reported adversely on the recommendations as noted in Representative Eckhardt's report to the Executive Committee on May 1, 1955 (Transactions, August, 1955, p. 746), and as reported in the May 1955 issue of the AGI News Letter. There was discussion of these matters, but no decision was reached.

Adjournment--The meeting adjourned at 17h 15m.

A. N. Sayre, General Secretary
Waldo E. Smith, Executive Secretary

APPENDIX 1--SECOND INTERIM OF THE SUBCOMMITTEE ON FORMAT

Walter B. Langbein, Chairman
Charles S. Gilman David G. Knapp

The Subcommittee has made a recommendation on the first part of its job, that is on the major aspects of format and on selection of a printer. In our interim report on May 8 [Trans. pp. 749-750, Aug. 1955], we reviewed the several alternatives and have concluded that letter press offers the most satisfactory method of meeting the specifications of the Executive Committee; for a more professional-appearing journal that specifically avoids our present monotony of font. In that report we outlined our major preferences on format; generally, two-column nine-point type for text, eight-point for subsidiary material.

Since that report we have visited the Kirby Lithographic Co., our present printer, to inform them of the prospective change. Our desire to improve the journal was sympathetically received, but quite understandably they asked whether we had considered using one of the local commercial firms who compose material (using varitype) for offset reproduction. This suggestion was made presumably to meet our desire to avoid a complex composing job on the AGU office and yet to combine the advantages of offset printing with the variety offered by the varityper. We obtained a quotation from a local composing company of $ 11.00 per page for straight text and $ 18.00 per page with formulas or tables or both. Since most of our pages have either formulas or tables, our average cost for this composition alone for an 160-page journal would be about $ 2500, which added to offset printing cost would be $ 4100, well above the estimates for letter press.

With regard to letter press, we had been negotiating with two firms, both of which have considerable experience with publication of scientific journals, and both enjoy high standing in the trade. Their tenders are of the same order of magnitude, and we had considerable difficulty in choosing between them. However, in setting down the merits and demerits of each as respects our journal we have concluded a recommendation in favor of the Waverly Press despite the fact that Company 'B' first brought the feasibility of letter press to our attention.

The considerations that led to our decision in favor of Waverly are:

(1) Waverly offered a two-column format that promised considerable saving in pages. Company B would do a two-column job, but was evidently not favorably inclined to that arrangement, and its estimate showed virtually no saving by its use.

(2) Waverly would provide an Old Style type face which in our judgment is more readable and yet affords a higher type density.

(3) Waverly offers two points of space between lines, compared with one point of lead that Company B provides.

(4) Waverly offers a page size 1/4 inch large each way than our present journal, Company B a smaller page. The large page permits a somewhat greater percentage utilization of the page.

(5) Waverly offers a book-sewn volume which will permit reader to lay the journal flat; a distinct and valuable convenience.

(6) The relative proximity of Waverly in Baltimore would enable more frequent contacts in case of snags in operations.

Although the general order of costs are the same, it is difficult to compare costs either in detail or overall. As submitted, the estimates are closely the same for the sample 160 page April 1954 issue (excluding program): Waverly $3283; Company B $3317.

However, in preparing this estimate, Waverly judged that by two-column format, only 138 pages would be needed. We believed that perhaps the sample issue was biased toward short formulas, other features potentially favorable to the two-column arrangement, and hence thought it wise to discount the savings. If so, then Waverly's estimate stands higher than that of Company B, depending on the extent to which one is inclined to discount the saving in pages. We have allowed $ 217 making their figure for purposes of comparison $ 3500.

We were ready with a recommendation in favor of Waverly Press when we were approached by the proprietor of Company C with prospect of a quotation substantially below that of the other firms. Company C submitted an estimate of $ 2892 for the sample April 1954 issue. The margin in favor of Company C is about $ 600 over Waverly and a little over $ 400 compared with Company B. Other things being equal the margin is substantial and would indicate a clear decision in favor of Company C. There are a number of reasons why an award to Company C was considered very critically. First, we received at no time a clear sample of work by Company C that meets our specifications that were clearly stated in our letters of July 15 and 20. On the other hand we have seen good quality work done by Company C for other customers (only one of which was mathematical and that was set up elsewhere) and we have the favorable testimony of these customers. It was evident that if we granted the contract to Company C, the Editorial Office would be involved in a considerable training period for that company and trips to their plant would be required at considerable cost. The Waverly Press has offered us a book-sewn job which is a very attractive but not essential feature. For Company C to supply book-sewn volumes would cost us from eight to ten cents a copy additional which would eliminate the margin in their favor. On the other hand we do not know at this time what the Waverly Press would quote us on a staple job but the differential would not be great. The Chairman is of the opinion that if the contract is awarded the price differential would be earned so to speak by the Executive Secretary in 'blood, sweat, and tears.' This was a critical decision to make. To save as much money as possible the Executive Secretary was perfectly willing to commit himself to whatever difficulties might be incurred in working with Company C. The saving of $ 500 or only $ 400 per issue means about $ 2500 or $3000 a year to the Union - a very considerable sum. But in making this choice we must consider the instructions from the Executive Committee for a high-quality Journal. By majority vote the Subcommittee recorded its decision in favor of award to The Waverly Press. Our job is now to review with that firm further details of schedule, design of cover, selection of paper stock, type, and other details.

APPENDIX 2--REPORT OF THE COMMITTEE ON AUDIT

Fiscal Year July 1, 1954 to June 30, 1955

A. Nelson Sayre, Chairman
A. G. McNish R. H. Weightman

Your Committee on Audit has examined the books of the American Geophysical Union for the fiscal year ending June 30, 1955, and finds them in agreement with the statement of the Union's finances supplied by the Executive Secretary.

At the beginning of the current fiscal year the Cash Assets of the Union amounted to $ 16,373.23, consisting of $ 14,292.32 in Cash Reserve, $ 900.00 held in reserve for the Directory, and $ 1,180.91 held in reserve for the Robert E. Horton Fund [see Trans., pp. 166-168, Feb. 1955]. At the end of the year the Cash Assets amounted to $ 17,075.33, consisting of $ 14,194.42 in Cash Reserve, $ 1,180.91 in the Robert E. Horton Fund, and $ 1,700.00 held in reserve for publication of the Transactions from funds made available by the National Science Foundation.

The Permanent Fund amounted to $ 12,080.24, an increase of $ 1,422.72, and the Emergency Fund amounted to $ 1,000.00, $ 61.36 previously shown as part of the Emergency Fund having been transferred to the Permanent Fund. An additional fund for the T. M. and E. Award contained $ 970.19, $ 758.53 of which had been received during the year.

Total receipts for the year amounted to $ 54,307.68 and the disbursements (including transfers to the Permanent and T. M. and E. Award Funds) amounted to $53,275.69, an excess of receipts over disbursements of $ 1,031.99. Records of accounts in the building and loan associations and in the Riggs National Bank were examined and found to agree with the statement made by the Executive Secretary. Your Committee also examined the bonds held by the Union and found them to agree in amount with that given in the statement.

Your Committee wishes to compliment the office of the Executive Secretary for the excellent condition of the accounts as submitted for audit.

Operating Statement

(Fiscal year ending June 30, 1955)

Receipts			
Grants			
National Research Council		$ 400.00	
National Science Foundation (for publication)		4,000.00	$ 4,400.00
Income			
Dues, 1952 and earlier	$ 275.00		
1953	332.50		
1954	4,134.88		
1955	27,488.08		
1956 et seq.	75.70		
Corporation Memberships	2,000.00		
Life Memberships	200.00	$34,506.16	
Sales of publications			
Transactions	$ 8,524.41		
Reprints	2,800.77		
Miscellaneous	75.30	11,400.48	45,906.64
Contributions to Permanent Fund			348.58[a]
Interest on Permanent ($283.89) and Emergency ($37.47) Funds			321.36
Contributions to T. M. and E. Award Fund			750.00[a]
Interest on T. M. and E. Award Fund			8.53
Air Force Contract			2,045.99[a]
Science Register			331.94[a]
Sale of equipment (Burroughs typewriter)			25.00[a]
Miscellaneous			169.64
		Total receipts	$ 54,307.68[b]

Disbursements

Publishing Transactions		
Printing	$ 10,382.62	
Preparing master copy	9,703.93	
Honoraria to editors	1,350.00	
Mailing	1,113.22	
Advertising expense	255.08[a]	$ 22,804.85[c]
Reprints		2,052.64
General expenditures (office of the Union)		
Salaries (including Federal Social Security)	$ 15,978.45	
Stationery and supplies	1,169.02	
Postage and communications	1,802.40	
Office equipment	505.10	19,454.97
Expenses, meetings		
Annual meeting	$ 1,035.84	
Regional meetings	47.50	1,083.34
Expenses, Section of T. M. and E.		58.49
Expenses, Section of Hydrology		9.79
Expenses, Committee on Membership		296.52
National Academy of Sciences pension plan		962.50
T. M. and E. Award Fund (investment, deposited with Liberty Building Assn.)		750.00[a]
Investment: Deposited with Northwestern Federal Savings and Loan Association as part of Permanent Fund		1,040.00[a]
Air Force Contract		2,293.95[a]
Bibliography of Hydrology, 1951-1954, contract		6.47[a]
Directory		1,781.64
Science Register		331.94[a]
Travel of officers (domestic)		62.57
Travel to IUGG assembly (drawn from Emergency Fund and later restored by Executive Committee action)		240.51
Bowie Medal		13.90
Miscellaneous		31.61
Total disbursements		$ 53,275.69

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[a] Non-budgeted items.

[b] Does not include $ 900.00 reserve for Directory set up in 1954 and disbursed in 1955.

[c] From National Science Foundation Grant $ 2,300.00 and from regular fund $ 20,504.85.

Excess of receipts over disbursements

Receipts	$ 54,307.68
Disbursements	53,275.69
Increase in liquid funds	$ 1,031.99

Statement of assets and liabilities as of June 30, 1955

Assets

Cash Reserve	$ 14,194.42		
Reserve for Transactions	1,700.00		
Robert E. Horton Fund	1,180.91	$ 17,075.33[d]	
Permanent Fund			
Series F bonds purchased prior to July 1, 1948 (maturity value $ 3,200), at cost	$ 2,368.00		
On deposits in Northwestern Federal savings and Loan Association as shown for July 1, 1955	9.613.41		
Total accumulated interest transferred from Emergency Fund on deposit in Prudential Building Association	98.83	12,080.24	
Emergency Fund			
On deposit in Prudential Building Association as shown for July 1, 1955		1,000.00	
T. M. and E. Award Fund			
On deposit with Liberty Building Association as shown for July 1, 1955		970.19	$ 31,125.76

Assets (concluded)			
		Forwarded	$31,125.76
Bills Receivable			
Dues			
1955 only	$ 4,654.00		
1954 and 1955	3,336.00	$ 7,990.00	
Publications			
Transactions (including subscriptions)	371.83		
Reprints	517.71		
Miscellaneous	4.00	893.54	8,883.54
Air Force Contract Receivable			630.70
			$ 40,640.00

Liabilities		
Bills Payable and advance payments		
Dues in advance (1956 et seq.)	$ 118.70	
Subscriptions in advance (1956 et seq.)	74.30	
Reprints paid in advance	76.00	$ 269.00
Surplus (Capital Account)		40,371.00
		$ 40.640.00

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[d]Riggs National Bank statement of June 30, 1955	$ 21,230.97
Less checks outstanding	4,155.64
	$ 17,075.33

APPENDIX 3--REPORT OF THE COMMITTEE ON STATUTES AND BY-LAWS

Ralph R. Bodle, Chairman
K. Hilding Beij John A. Fleming

In accordance with the instructions from the Executive Committee at its meeting on October 15 [see page 1111 of this issue], the Committee on Statutes and By-Laws has revised By-Law (18) chiefly for the purpose of providing, under certain circumstances, for the signature of the Executive Secretary on the accounts of the Union. In rewriting this, the Committee has also made other slight changes to make for smoother reading without changing the thought or intent. The new By-Law, which is deemed to have Executive Committee approval, is here officially published as required by Article 13 of the Statutes as revised to April 30, 1955 [see Trans., June, 1955, pp. 564-568], and is as follows:

(18) The General Secretary elected by the Union shall be responsible to the Executive Committee of the Union for the general administration of the Union's activities as determined by the Executive Committee of the Union. He shall serve without honorarium, and shall exercise general supervision over the Executive Secretary. He shall serve as Treasurer of the Union, receive and disburse funds in accordance with the instructions of the Executive Committee of the Union, sign checks as General Secretary on the accounts of the American Geophysical Union with depositories approved by the Executive Committee of the Union, and shall provide a surety bond in a sum set by the Executive Committee of the Union and at the expense of the Union, for funds of the Union under his control. If the General Secretary is absent or incapacitated, the President, or, if he is absent or incapacitated, the Vice-President, shall sign checks against the Union accounts. The General Secretary, or the President or the Vice-President serving as Treasurer in his capacity, may empower the Executive Secretary to sign checks against the accounts of the Union during their terms of office. The President, the Vice-President, and the Executive Secretary shall furnish surety bonds in the same manner and amount as the General Secretary.

SPECIAL ANNOUNCEMENTS

Student membership now available in AGU--Attention is called to the fact that the amendments to the Statutes and By-Laws approved by vote of the membership early in 1955 provided for the establishment of a Student grade of membership [see the revised Statutes and By-Laws, Trans., June, 1955, p. 565, Art. 3 (f) and p. 567, By-Law (2)]. Dues for those who qualify under Article 3 (f) have been set by the Executive Committee at $3.00 for the calendar year 1956. Students applying for such membership should do so on the regular 'Proposal for Membership' form, available from the office of AGU, modifying the notation at the head appropriately. The certificate cited should be sent in with the application for membership, and payment should be included.

SPECIAL ANNOUNCEMENTS

LIST OF OFFICIAL NOMINEES FOR OFFICERS OF THE UNION, OF THE SECTIONS, AND OF THREE OF THE REGIONAL COMMITTEES FOR THE TRIENNIUM JULY 1, 1956 TO JUNE 30, 1959

Union or Section	President	Vice President	Secretary[a]
Union	Horace R. Byers Maurice Ewing	Lloyd V. Berkner Ross R. Heinrich	J. Wallace Joyce A. Nelson Sayre
Geodesy	Milton O. Schmidt	Philip C. Doran	Frank L. Culley
Seismology	Hugo Benioff	Leonard M. Murphy	James A. Peoples, Jr.
Meteorology	Helmut E. Landsberg Jerome Namais	Jule G. Charney Thomas F. Malone	Woodrow C. Jacobs
Terrestrial Magnetism and Electricity	Carl W. Gartlein Henry R. Joesting	Leroy R. Alldredge H. Herbert Howe	R. E. Gebhardt J. Virginia Lincoln
Oceanography	Dale F. Leipper Roger R. Revelle	John D. Isaacs Henry Stommel	Clifford A. Barnes Donald W. Pritchard
Volcanology, Geochemistry, and Petrology	Brian H. Mason J. Frank Schairer	John Verhoogen Francis G. Wells	L. Thomas Aldrich John C. Maxwell
Hydrology	Ray K. Linsley	William C. Ackermann Harry F. Blaney	Edward A. Colman Ralph N. Wilson
Tectonophysics	Harry H. Hess Louis B. Slichter	James R. Balsley, Jr. Patrick M. Hurley	H. Richard Gault Benjamin F. Howell, Jr.

In addition, in Tectonophysics, two members are to be elected to the Executive Committee of the Section. The nominees are Marland P. Billings, Richard H. Jahns, and Francis P. Shepard.

Nominees for Regional Committees

Pacific Southwest Regional Committee (Arizona, California, and Nevada)

Hydrology (three to be elected): Lloyd D. Doneen, John F. Mann, Jr., Harlowe M. Stafford, and David K. Todd.

Meteorology (three to be elected): R. Corday Counts, Jr., Robert E. Holzer, and Eugene N. Bollay

Pacific Northwest Regional Committee (Idaho, Montana, Oregon, Washington, and Wyoming; seven to be elected): Franklin I. Badgley, Clifford A. Barnes, Norbert H. Leupold, Fred Natella, Milton S. Sachs, Vail P. Schermerhorn, and Wilbur D. Simons

North Central Regional Committee (Iowa, Kansas, Minnesota, Missouri, Nebraska, North Dakota, and South Dakota; six to be elected): Alvin G. Anderson, Edward M. Brooks, C. Robert Elford, Russell G. Mann, Everett V. Richardson, and Tarmo Waara

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[a] For General Secretary in the case of the Union.

Explanatory note--In accordance with the Statutes and By-Laws as amended to April 30, 1955, elections by mail ballot are to be held in the first part of 1956. The Committees on Nominations for the Sections were published in the *Transactions* of June 1955 in the minutes of the Sections, pages 551-559. The Executive Committee of the Union has established procedures for nomination and election of officers of the Union, as published in the December 1946 issue of the *Transactions*, page 910. These are as follows: (1) Nominations shall be initiated by a small Nominating Committee consisting of three or five members, appointed by the President. (2) At least two persons shall be nominated for each of the offices of President, Vice President, and General Secretary. (3) Such nominations shall then be submitted by the Nominating Committee to the Executive Committee, which body may accept the report, or add other nominees for such offices. It will then proceed to select by secret ballot not less than two official nominees for each office. (4) Such nominations shall then be announced to the membership, sufficient time being provided before election to permit further nominations by petition when signed by one per cent (50 at present) of entire membership, it being mandatory that nominations by petition be added to the official nominations (see (9), below). Ballots containing official nominees and those submitted by petition shall be mailed to the active membership and such ballots, postmarked before a specified date, shall be marked and forwarded by the membership to the General Secretary. (6) The General Secretary within ten days after the specified date shall turn over all such ballots for tallying to a Committee of Tellers consisting of one member selected from each of the eight Sections and one member from the Executive Committee. (7) The Committee of Tellers shall make report to the General Secretary within ten days, showing the result of the ballot. (8) A plurality of votes cast shall elect. (9) Consent of each candidate is to be obtained before placing his name on the ballot. (10) The Sections shall be urged to adopt similar procedures.

Similar Section procedures were established and were published in the Transactions of December 1946, with amendments covering Seismology and Hydrology in the Transactions of August 1949, page 627. In the summer of 1952, the Executive Committee of the Section of Geodesy voted to permit the nomination of one candidate for each office of that Section. The procedures will not be repeated in full here. All provide for nominations by petition, the number of member petitioners affiliated with the Section being as follows: Geodesy, ten members; Seismology, 13 members; Meteorology, 25 members; Terrestrial Magnetism and Electricity, one per cent of those affiliated with the Section (11 members at present); Oceanography, ten members; Volcanology, one per cent of those affiliated with the Section (nine members at present); Hydrology, 25 members; and Tectonophysics, 15 members.

Please note that nominations by petition must include written consent from the nominee, to be transmitted to the office of AGU with the petition.

The following schedule for nominations and elections has been established:

By November 10, 1955, steps (1) to (3) and step (9) of procedure must be complete for the official nominees.

In Transactions of December, 1955, publish list of official nominees with explanatory note.

By February 1, 1956, nominations by petition must be in the office of AGU with written consent of nominees.

By March 1, 1956, ballots carrying names of official and petition nominees, will be mailed to the membership. A brief biographical sketch relating to each nominee will accompany, but not be a part of, the ballot.

On March 31, 1956, balloting will close. Ballots must be postmarked not later than that date and be received in the office of AGU not later than April 4, 1956, in order to be counted.

By April 10, 1956, ballots will be turned over to the Committee of Tellers.

By April 20, 1956, results of tally will be turned over to the General Secretary, results to be announced at the Annual Meeting April 30 - May 2, 1956, and published in the Transactions in June, 1956.

In addition to the election of Union and Section officers, three Regional Branches will hold elections by mail ballot, the nominees to be voted upon only by members in those Regions. The names are also shown in the accompanying table.

Waldo E. Smith, Executive Secretary

Pacific Southwest Regional Meeting, University of California at Los Angeles, January 26-27, 1956-- The program for this meeting is now largely complete. Arthur F. Pillsbury, Professor of Irrigation and Soils at UCLA, is General Chairman of the meeting with Vito A. Vanoni, Professor of Hydraulics at California Institute of Technology, as Program Chairman and with James G. Edinger, Professor of Meteorology at UCLA, arranging the program in Meteorology. Martin R. Huberty, Professor of Irrigation at UCLA, is Chairman of the Regional Committee; R. Corday Counts, Jr., U. S. Weather Bureau at Burlingame, California is Regional Secretary. Interested persons should get into touch with one of these.

Thirty-Seventh Annual Meeting, Washington, D. C., April 30 to May 2, 1956, with Symposium on the Antarctic, April 26-27, and with meetings in Meteorology extending to May 4--Your attention is called to the extended notice concerning this meeting on pages 935-936 of the October issue of the *Transactions*. Note that in general titles and abstracts of papers for the program should be sent in as soon as possible to the appropriate person, and in general not later than March 5, 1956. The following developments are especially noted. For symposia being planned in connection with the program in meteorology, however, the closing date is February 1. Suggested symposia titles in this group are: Data Processing; Pollution of the Air; Atmospheric Electricity; The Hurricane; Semantics of Issuing Weather Information and Forecasts; Utilization of Non-Standard Observations; and Eddy Transport within the Boundary Layer. The scientific sessions in meteorology will be held jointly with the American Meteorological Society, and, as noted in the heading of this announcement, will extend through May 4. Titles and abstracts for all papers in meteorology, including those for the symposia may be sent to Secretary Woodrow C. Jacobs, as noted in the October issue, or to Joseph Smagorinsky, General Circulation Research Section, U. S. Weather Bureau, Washington 25, D.C. Another symposium to be integrated into the programs in meteorology and oceanography will be on the subject of A New Look at Ocean Currents with Emphasis on Transients and is being arranged by the AGU-AMS Joint Committee on Interactions of the Atmosphere with the Sea. Titles and abstracts for contributions for this should be sent to Chairman, Charles C. Bates, at 7810 Gateway Blvd., S. E., Washington, D. C., by February 1, 1956.

Abstracts must be informative and concise; not more than 150 words. Longer abstracts will be cut down or omitted at the discretion of the program editor. Remember that Sections may close programs prior to March 5 and that February 1 is the closing date for a number, so send information in early. Complete manuscripts should be in the AGU office by April 15, with advice as to whether the paper is being submitted for the *Transactions* or only for information. If the former case, three copies, complete with figures and tables, should be sent, double-spaced, and in general accordance with AGU's "Suggestions to Authors." Also send word concerning projection equipment required. A standard-sized (3 1/4 × 4 inches) slide projector will normally be available, but other facilities will be provided only upon word of requirements. Communications should be sent to the appropriate Section Secretary or Program Chairman (see October issue, p. 636, with above modifications) or to the AGU office. If you do not have experience in proper preparation of figures and tables for the making of slides, write to the AGU office requesting information on this. The one general rule, however, is to avoid crowding and attempting to show too much on one slide. More than two or three curves on one slide tend to be confusing. Use good-sized lettering.

In preparing a paper for presentation, keep in mind that the requirements are quite different from those for publication. A paper for presentation might be compared to a thread or chain, while a published paper is more on the order of a fabric. And, in presentation, keep in mind that you should face the audience and speak slowly, distinctly, and briefly, and avoid complicated mathematics. The mathematical presentation should appear in the published paper.

Block bookings have been made at three hotels as follows:

Roger Smith Hotel, Pennsylvania Avenue at 18th Street, N. W.

Willard Hotel, Pennsylvania Avenue at 14th Street, N. W.

Raleigh Hotel, Pennsylvania Avenue at 12th Street, N. W.

Most of the block-booked rooms are in the Roger Smith Hotel (the one nearest the National Academy of Sciences where most of the sessions will be held), and the Willard Hotel. Make your room reservation early directly with the hotel of your choice, citing the AGU block booking if you write to one of the three hotels noted.

Notice of intent to change By-Law (18)--The changes in the Statutes and By-Laws approved by the membership early this year provide that the Executive Committee may now, by procedures outlined in Article 13 (b) of the Statutes [see Trans., June 1955, p. 566] amend the By-Laws. Notice is hereby given of plans to change By-Law (18) as set forth in the Minutes of the Executive Committee of October 15, 1955 (see pages 1111 and 1118 of this issue) to provide, under certain circumstances, for the signing of checks by the Executive Secretary on the accounts of AGU. It is anticipated that further action on this matter will be taken at the next meeting of the Executive Committee in late April, 1956.

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